

# Design of a Cusped Field Plasma Thruster

Joseph Richard Conte III

Submitted to the Department of Mechanical Engineering  
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

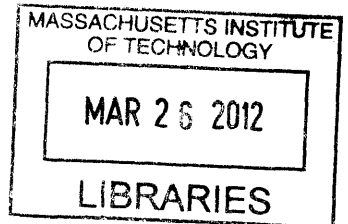
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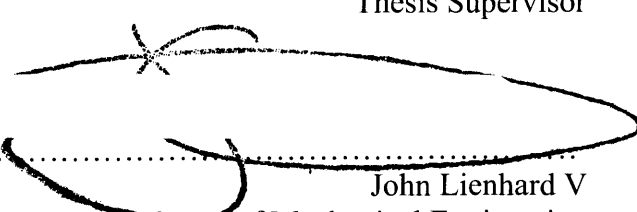
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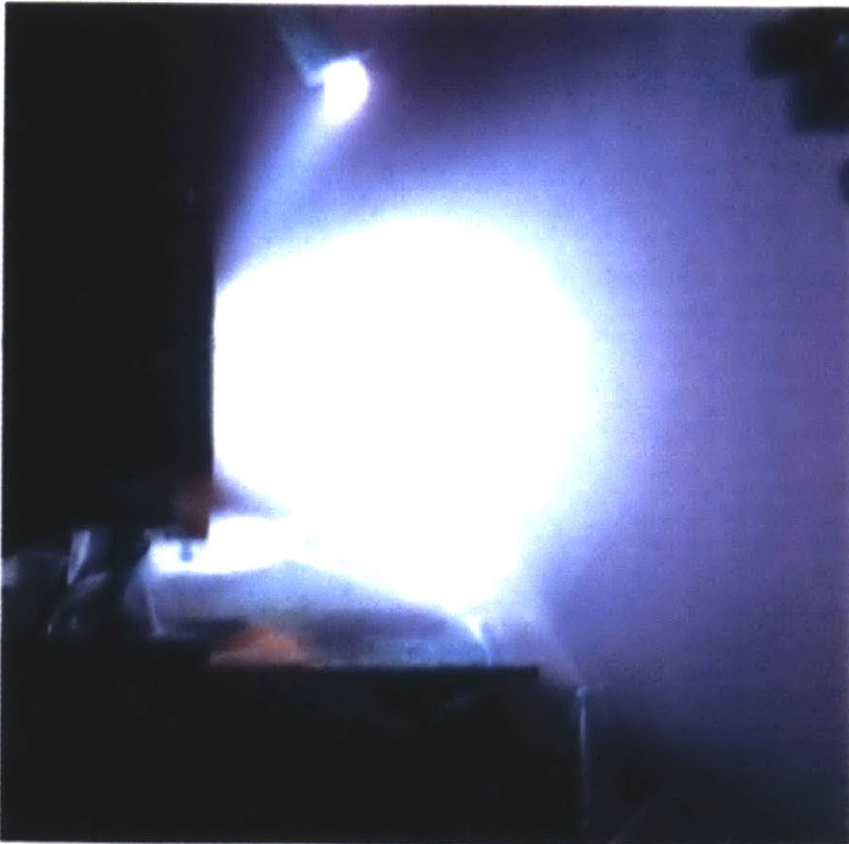
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By  
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## Abstract

A plasma space propulsion thruster has been designed. It is classified as a Cusped Field Thruster (CFT), which refers to the geometry of the magnetic field that influences the flow of electrons and ions. The thruster was modeled after an original Diverging Cusped Field Thruster (DCFT) developed at MIT's Space Propulsion Laboratory. There are several improvements (including a flat downstream separatrix) that are aimed at increasing performance. In general, plasma thrusters have applications in satellite trajectory adjustment and deep space probes because of their superior fuel efficiency compared to chemical thrusters.



The original DCFT firing.



# Acknowledgements

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# Introduction

## 1.1 Electrostatic Propulsion

There are currently two categories of spacecraft propulsion: chemical and electric. Chemical thrusters operate by releasing energy via chemical reaction. The expanding byproducts of the reaction are focused and expelled from the thruster, creating a force in the opposite direction by conservation of momentum. Electric thrusters make use of electric fields to accelerate charged particles, also creating a propulsive force by conservation of momentum. Electric thrusters can have a much higher propellant efficiency than chemical thrusters, at the expense of lower thrust. This makes them ideal for applications such as satellite trajectory adjustment and deep space exploration, where high acceleration is not necessary but reduced propellant use is important. This is characterized by the specific impulse  $I_{sp}$ , which is the ratio of thrust  $T$  to the mass flow rate of the thruster  $\dot{m}$ , divided by the acceleration of gravity on earth  $g$ .

$$I_{sp} = \frac{T}{\dot{m}g} \quad (1)$$

It can be shown that a spacecraft with a higher specific impulse will deplete less propellant in order to achieve a certain change in velocity  $\Delta V$  in a zero-resistance environment.<sup>5</sup>

$$M_p = M_0 \left( 1 - e^{-\frac{\Delta V}{gI_{sp}}} \right) \quad (2)$$

$M_p$  is the mass of propellant, and  $M_0$  is the initial mass of the vehicle. Typically, chemical thrusters have a specific impulse of less than 450 s, while electric thrusters can exceed a specific impulse of 5,000 s.<sup>1</sup> This leads to a much more efficient use of fuel for electric thrusters.

## Background

### 2.1 Review of the Original DCFT

This design of the new cusped field thruster was aimed at making improvements to the original Diverging Cusped Field Thruster (DCFT) developed at the MIT Space Propulsion Laboratory.<sup>1</sup>

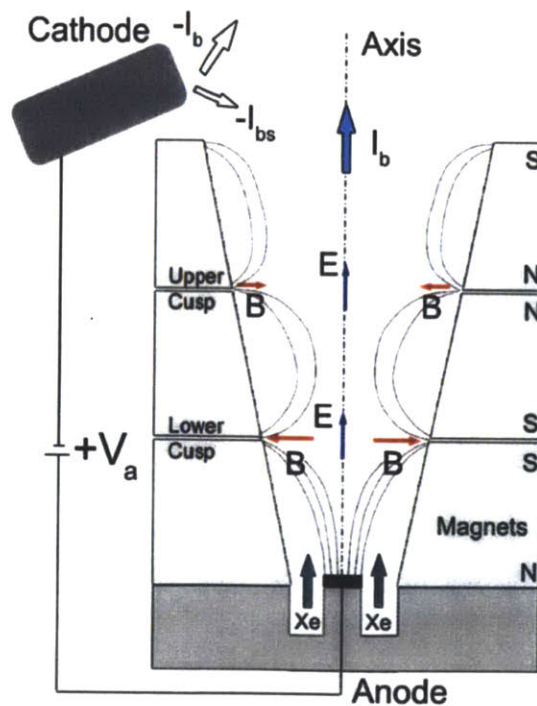


Figure 1: A schematic of the DCFT.

The design features three permanent magnets arranged with alternating polarities. This pattern results in two strong cusps in the space where the magnets meet. The steel base is designed to channel the magnetic field lines so that there is a high field strength and gradient at the anode.

The thruster operates by accelerating ions out of the chamber, producing thrust. To begin this ionization process, electrons from the cathode travel into the thruster by moving along the magnetic field lines, in the direction of the electric field that is created by the potential difference between the anode and the cathode. This movement is governed by the Lorenz equation.

$$\vec{F} = m \frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (3)$$

Simultaneously, xenon gas is diffused into the thruster. When an electron collides with an atom of xenon, another electron and a xenon ion are produced. Most of this ionization takes place near the cusps. The reason for this phenomenon is that there is a magnetic mirror at this location. A magnetic mirror is a region in which the magnetic field strength is concentrated along a magnetic field line. The electrons are magnetically repelled from this region and electrostatically repelled by a thin sheath near the wall. They tend to get trapped between the emitting cathode and the downstream cusps, and also in between cusps. The electrons will oscillate for many cycles before they escape by crossing the magnetic field lines due to scattering events. This oscillation allows more electron movement within the thruster before they are absorbed by the anode, causing more of the xenon gas to be ionized. These xenon ions are then accelerated out of the thruster by the electric field. This creates thrust according to the mass of the particles leaving the thruster.

$$\vec{T} = \sum \dot{m}_{out} \vec{v}_{out} - \sum \dot{m}_{in} \vec{v}_{in} \quad (4)$$

In this equation,  $\dot{m}$  is the mass flow rate of the particles, and  $v$  is the velocity at which they are traveling. Since the momentum flux of the ions exiting the thruster is much greater than the ions entering the thruster, there is a net thrust in the desired direction.

It is important to note that without further intervention, the ions would eventually make their way back to the thruster because of their opposite charges. This effect is avoided by the cathode emitting additional electrons that neutralizes the stream of ions leaving the thruster.

## 2.2 Design Considerations

The main purpose of creating the new cusped field thruster was to attempt to boost thrust and efficiency by altering the magnetic field topology of the original thruster. The magnetic field has the greatest influence on ionization because electrons (which cause the ionization) are strongly affected by it. The ions themselves are usually dominated by the electric field because of their larger mass. Below is a topological graph of the magnetic field strength and field lines created by the thruster.

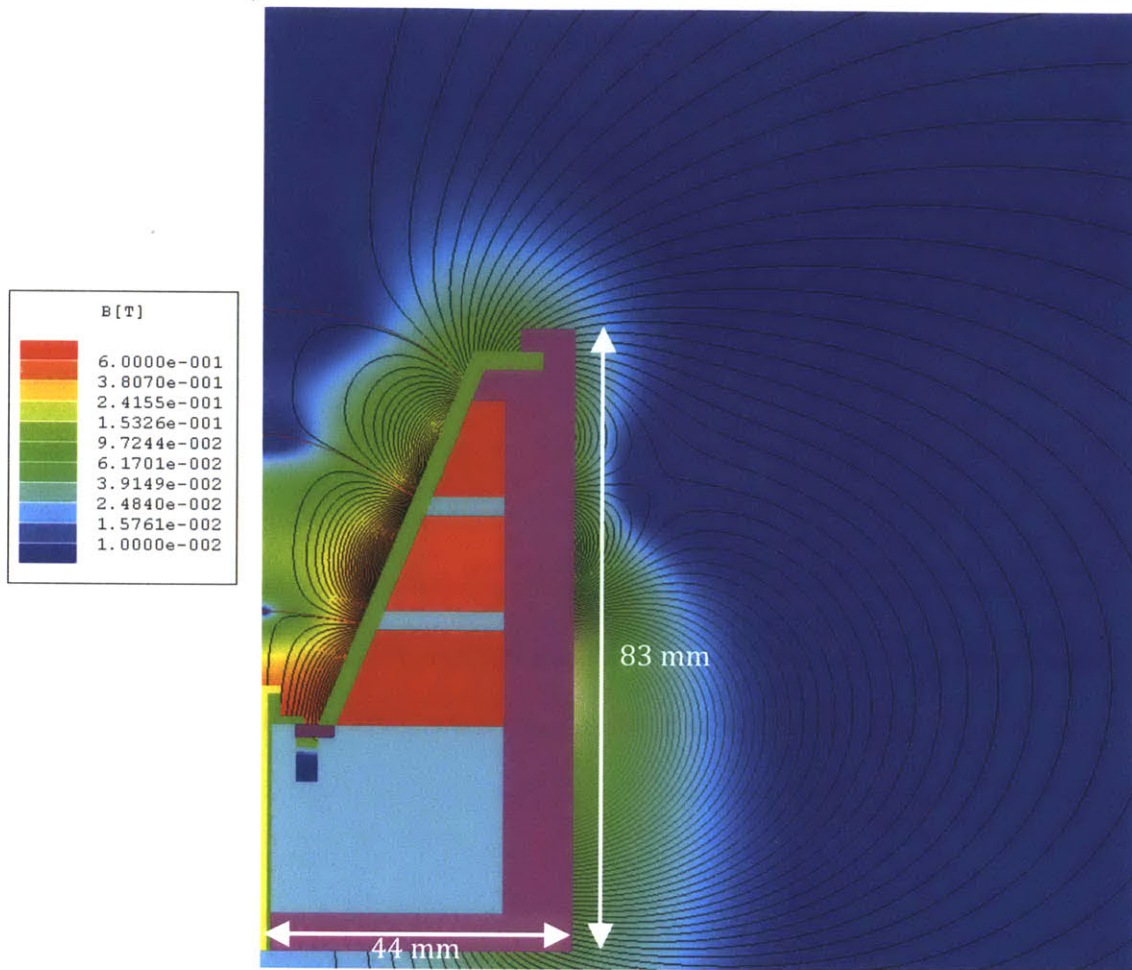


Figure 2: Magnetic field strength and flux lines of the DCFT in a vacuum. The red lines represent separatrixes.

There are several important factors to consider when designing a plasma thruster of this type.

The new design sought to incorporate and make improvements in the following five areas.

- Field lines that begin out of the plume and end at the downstream cusp. This allows for the cathode to be placed outside of the plume to reduce cathode erosion.
- High field strength and gradient at the cusps. This confines the electrons to that region through magnetic mirroring, allowing for greater ionization.

- High field strength and gradient at the anode. This inhibits electron flow to the anode through magnetic bottling, allowing for greater ionization.
- Low field strength outside the mouth of the thruster. It has been observed experimentally that this increases the fraction of xenon ionized.
- Flat downstream separatrix. A separatrix in this context is defined as a curved surface that separates magnetic flux lines originating from the cusps. Magnetic field lines on one side of the separatrix terminate at one end of a magnetic pole, while field lines on the other side terminate at the other end. It has been observed experimentally that ions are ejected normal to the plane of the downstream separatrix. A flat downstream separatrix will increase thrust and efficiency by channeling more ions along the line of propulsion. The original DCF thruster lacks this feature, so it was given top priority in the redesign effort.

# Design

## 3.1 Permanent Magnet and Steel Placement

The cusped field thruster (CFT) was designed to incorporate certain improvements from the original thruster that would increase thrust and efficiency. The first step was to create a geometry of permanent magnets and steel that would produce a magnetic field conducive to maximizing xenon ionization and expelling the ions efficiently. Ansoft Maxwell 2D magnetic software was used in the design process that included 481 iterations.

<b>Color</b>	<b>Material</b>
Red	Samarium Cobalt Magnets
Blue	Steel
Pink	Aluminum
Purple	Porous Ceramic
Green	Boron Nitride
Yellow	Graphite

Table 1: Color code of the Ansoft Maxwell 2D simulations.

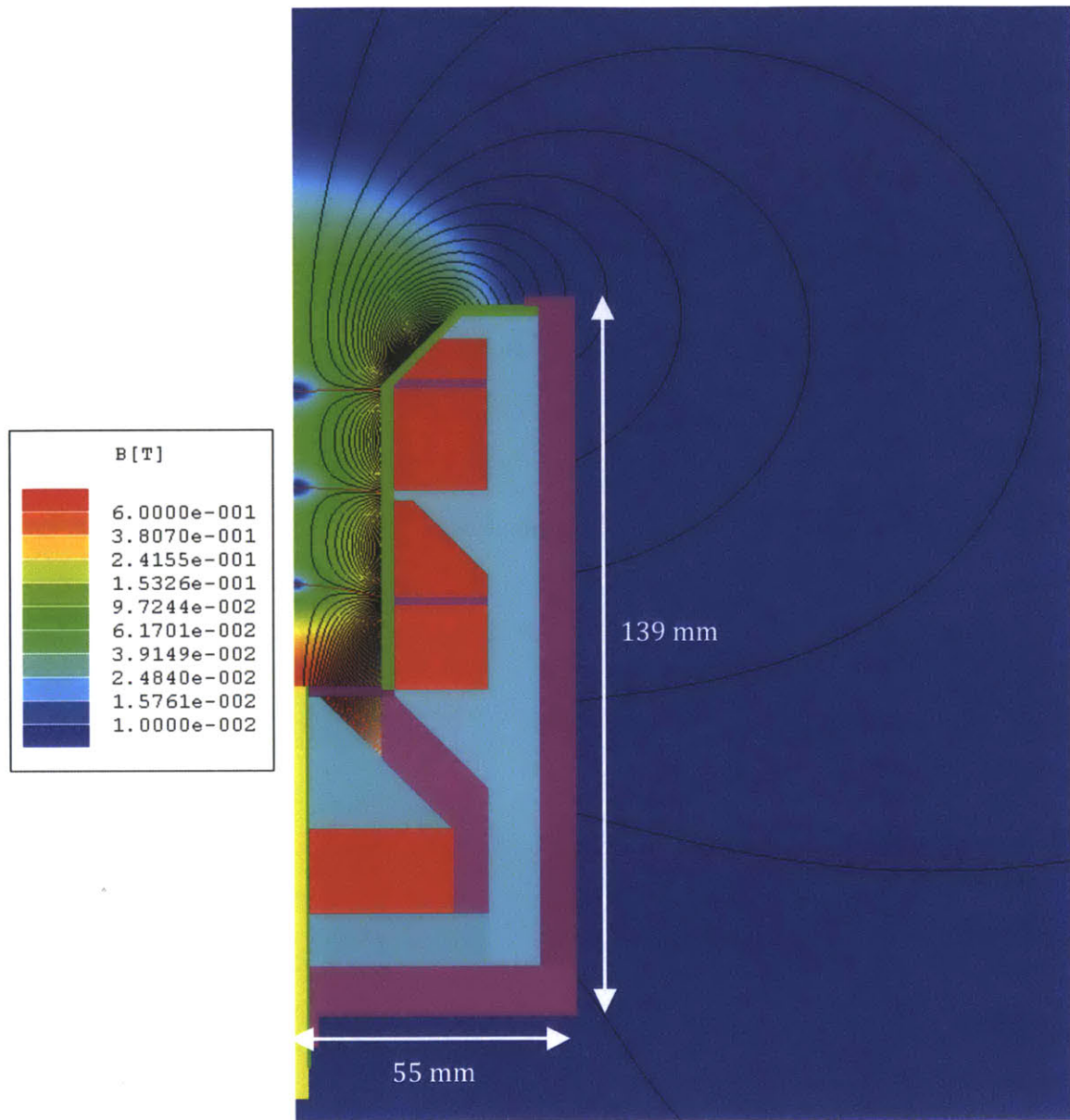


Figure 3: Magnetic field strength and field lines of the Cusped Field Thruster. The red lines represent separatrices.



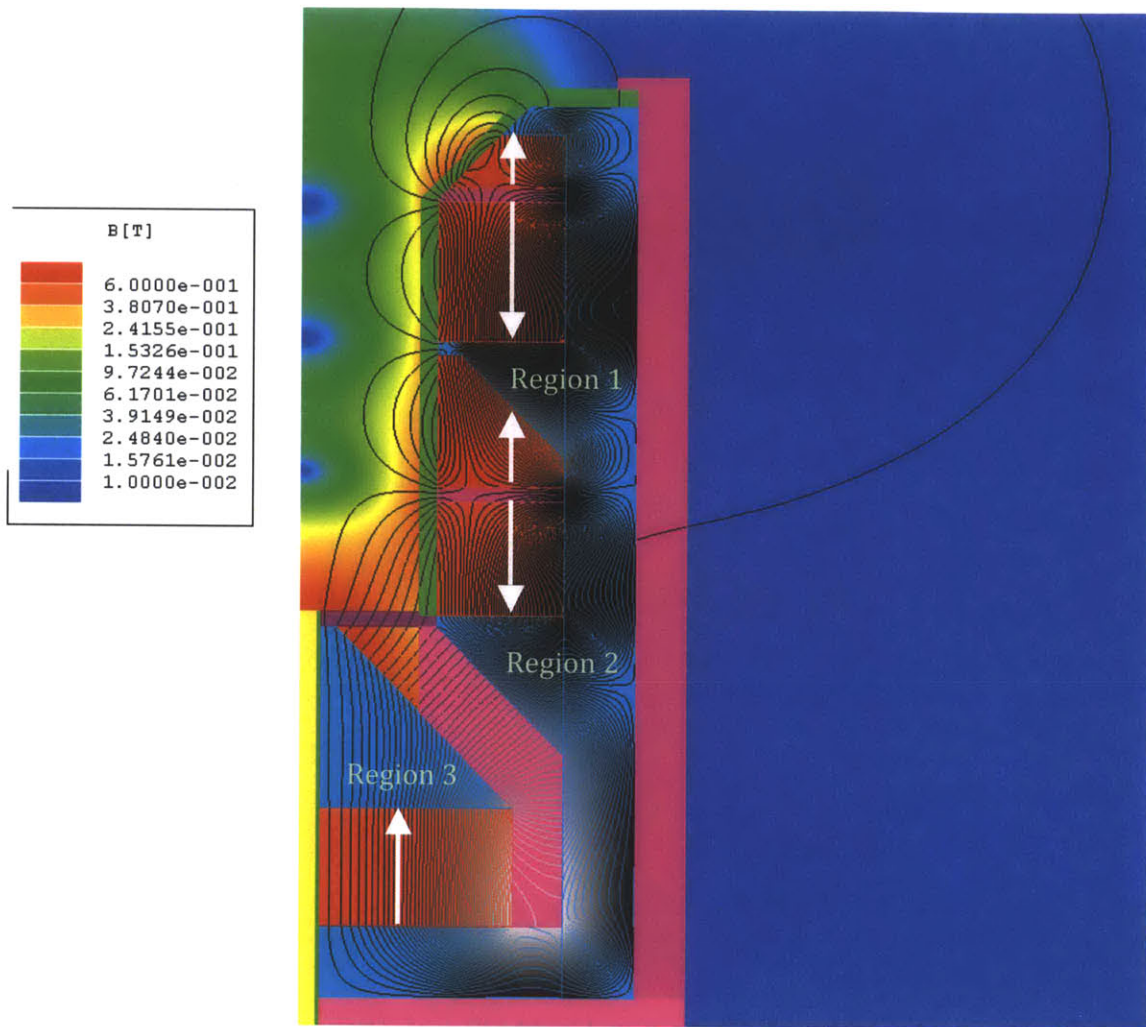


Figure 4: Magnetic field strength and field lines of the Cusped Field Thruster, also showing field lines that pass through solid objects. White arrows denote magnet polarity.

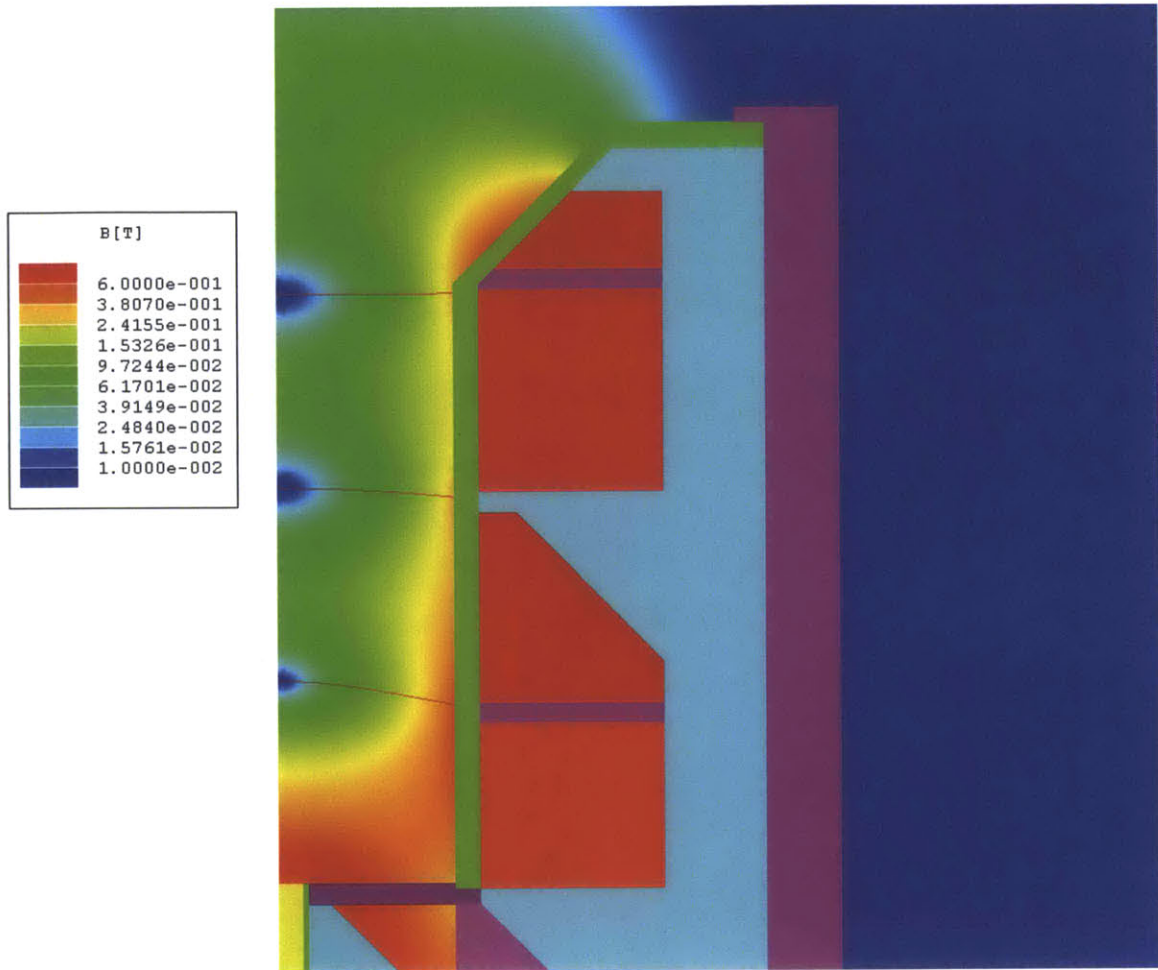


Figure 5: Magnetic field strength of the Cusped Field Thruster. The red lines represent the separatrices.

The design shown in the figures was selected because it exhibits almost all of the magnetic field properties outlined in the Design Considerations section. Its main feature is the flat downstream separatrix, seen in Figures 3 and 5. This comes at the expense another design objective: low field strength outside the mouth of the thruster. The diameter of the chamber was set to the average diameter of the original thruster's chamber (17 mm). All other dimensions were selected to provide desirable field topology. An effort was also made to match the field strength along the wall to that of the original thruster.

Another key difference is that the CFT is not divergent. One problem with the original thruster was that it exhibited oscillatory behavior in the anode current while running in a low current mode.<sup>1</sup> There is some evidence to suggest that increasing exit plane density favors operation in a non-oscillatory low current mode.<sup>12</sup> It is thought that this mode of operation will be more efficient and less erosive. Furthermore, a cylindrical geometry is more modular and allows for simpler replacement of parts and more extensive modifications.

This thruster has a field strength of 0.29 Tesla at the middle cusp as well as a large gradient. At the anode, the field strength is 0.46 Tesla and there is also a large gradient there. These features will enhance xenon ionization through magnetic mirroring and magnetic bottling.

Notably, two more magnets have been added since the original design. The top magnet serves the purpose creating an additional, flat separatrix. It also shapes the field lines outside the thruster in such a way that the cathode can be placed outside the plume. The magnet below the anode is used to boost the magnetic field strength and gradient at the anode.

The steel enclosure has some special features that make this favorable field topology possible. First, Region 1 (seen in figure 4) exists for the purpose of minimizing saturation. It was found that when the middle steel spacer had no incline, there was insufficient material for the field lines to travel into the outer part of the casing. Region 2 exists to divert field lines away from the north pole of the magnet located directly above it so that they can be channeled along the steel casing to the south pole of the anode magnet, creating a more efficacious magnetic circuit. Following

this circuit out of the anode magnet, the field lines are focused through Region 3, which is responsible for directing field lines into the chamber and into the middle cusp. This promotes high field strength and gradient at the anode.

### 3.2 Demagnetization

As the thruster was being designed, there was a concern that because of the proximity of the magnets, some of them may become demagnetized. To ascertain whether this would happen, magnetic property data were taken from Dexter Magnetic Technologies for Samarium Cobalt Type 3212 magnets.

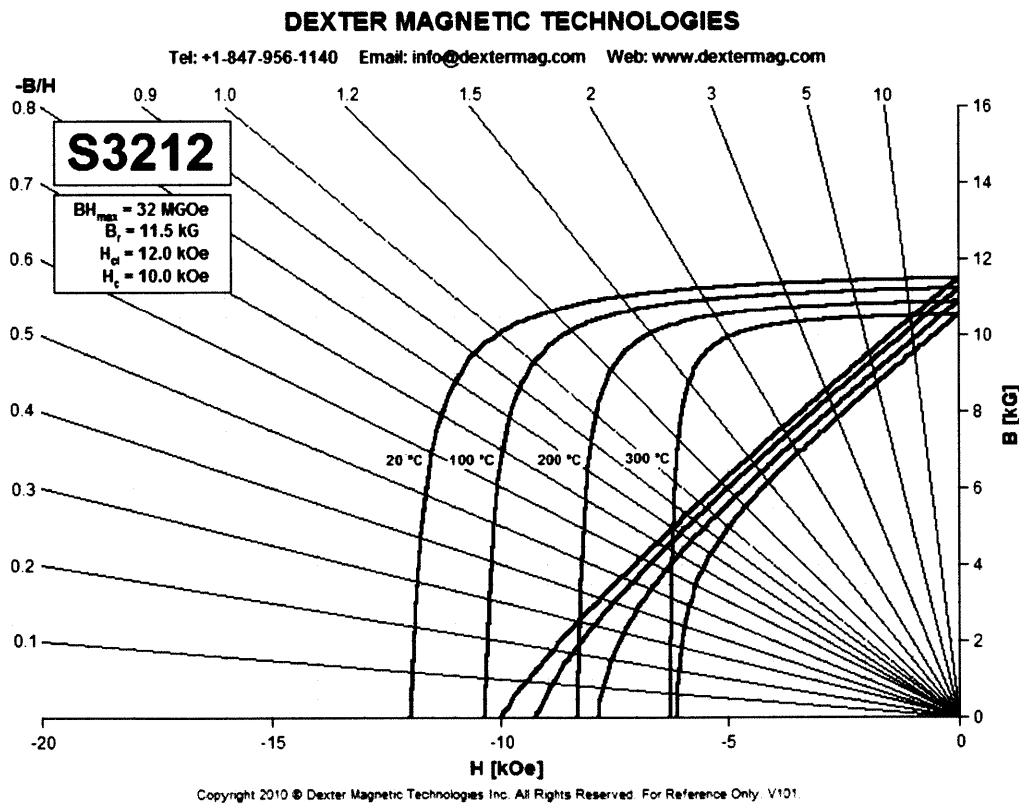


Figure 6: B-H Curve of Samarium Cobalt Type 3212.

Magnetic field data of the thruster were taken from the Ansoft Maxwell 2D simulation. The quantity  $B/H$  was computed at all points within the magnets. This quantity was compared to the  $B-H$  curve at 300 degrees C. Since no point within the magnets had the quantity  $B/H$  smaller than 2 (an arbitrary point taken from the curve, below which a small change in  $H$  will have a large change in  $B$ ), this magnetic arrangement is stable and no demagnetization due to proximity will occur.

### **3.3 Thermal Conditions**

Measurements from the DCFT indicate its magnets attain a temperature of between 200 and 400 degrees C during operation. Even higher temperatures are thought to be attained at the anode, although this has never been measured directly. Since all permanent magnets demagnetize when they reach a certain temperature, a thermal study was performed on the CFT in order to predict whether any of the magnets would demagnetize due to overheating. SolidWorks Simulation software was used for this study.

The material properties for thermal conductivity and specific heat of the thruster's components were input into SolidWorks. These properties were obtained online from academic papers and industry data sheets. It is known that there is thermal resistance not only in the materials of an assembly, but also in the interface between the materials. This can have a large effect on thermal conditions. The estimated contact resistance was taken to be  $0.01 \text{ m}^2 \cdot \text{K/W}$ .<sup>6</sup>

The thermal loads were chosen based on estimates from the original thruster. These were input into SolidWorks in terms of thermal powers. 30 W were input into the exposed area of the anode. An additional 50 W were input into the cylindrical region of the erosion shield.

Heat leaves the thruster in the form of radiation. All exposed surfaces were set to radiate to an ambient temperature of 293 K. Metal parts were assigned an emissivity of 0.2, and ceramic and graphite parts were assigned an emissivity of 0.85. Radiation between surfaces was taken into account.

Heat also leaves the thruster due to conduction. Heat is transferred from the base and the wire connected to the anode to the ground. To simulate the ground, an aluminum cube 100 mm in length was constructed under the thruster's base. The bottom surface was set to 293 K. It was found that from 100 mm and larger, the size of the cube effected the results by no more than 5 degrees K. In addition, a 22 gauge copper wire 1 meter in length was constructed and attached to the end of the anode. The far end of this wire was set to 293 K.

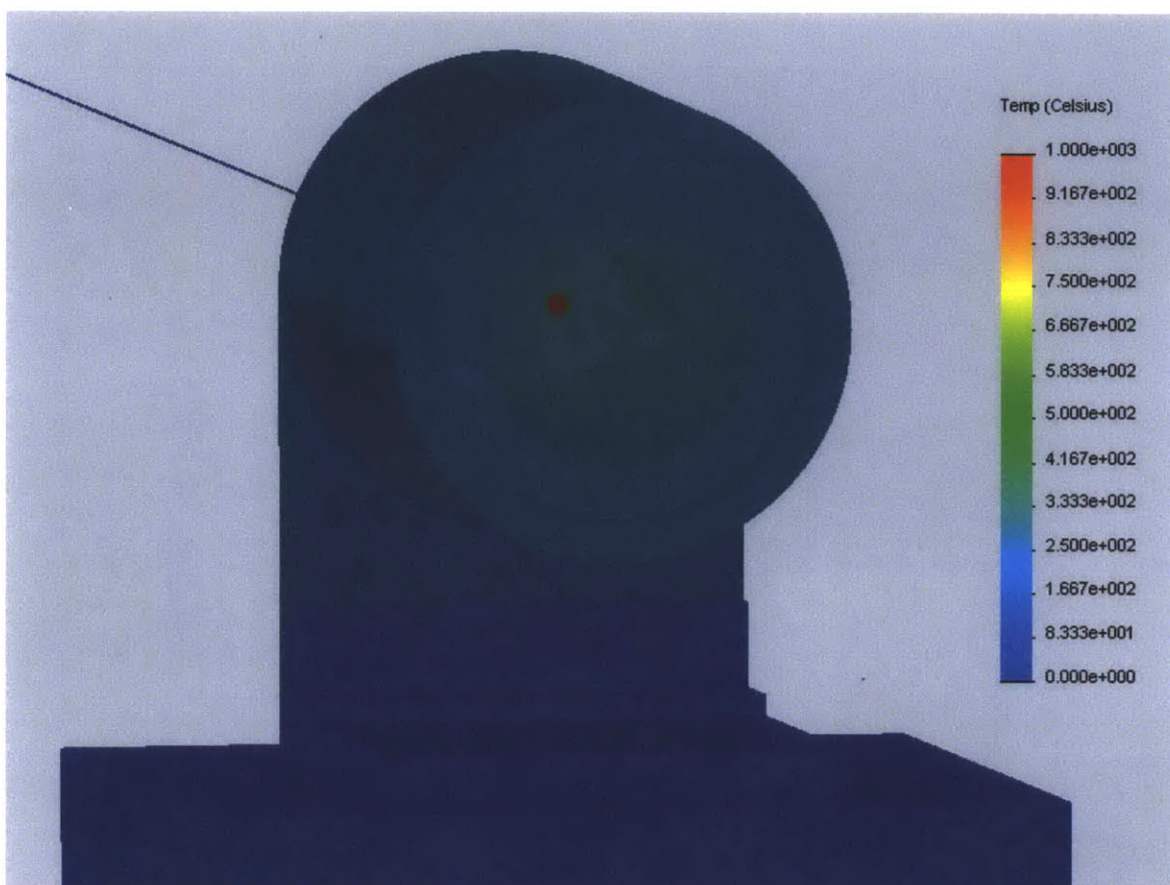


Figure 7: Thermal exterior of the Cusped Field Thruster.



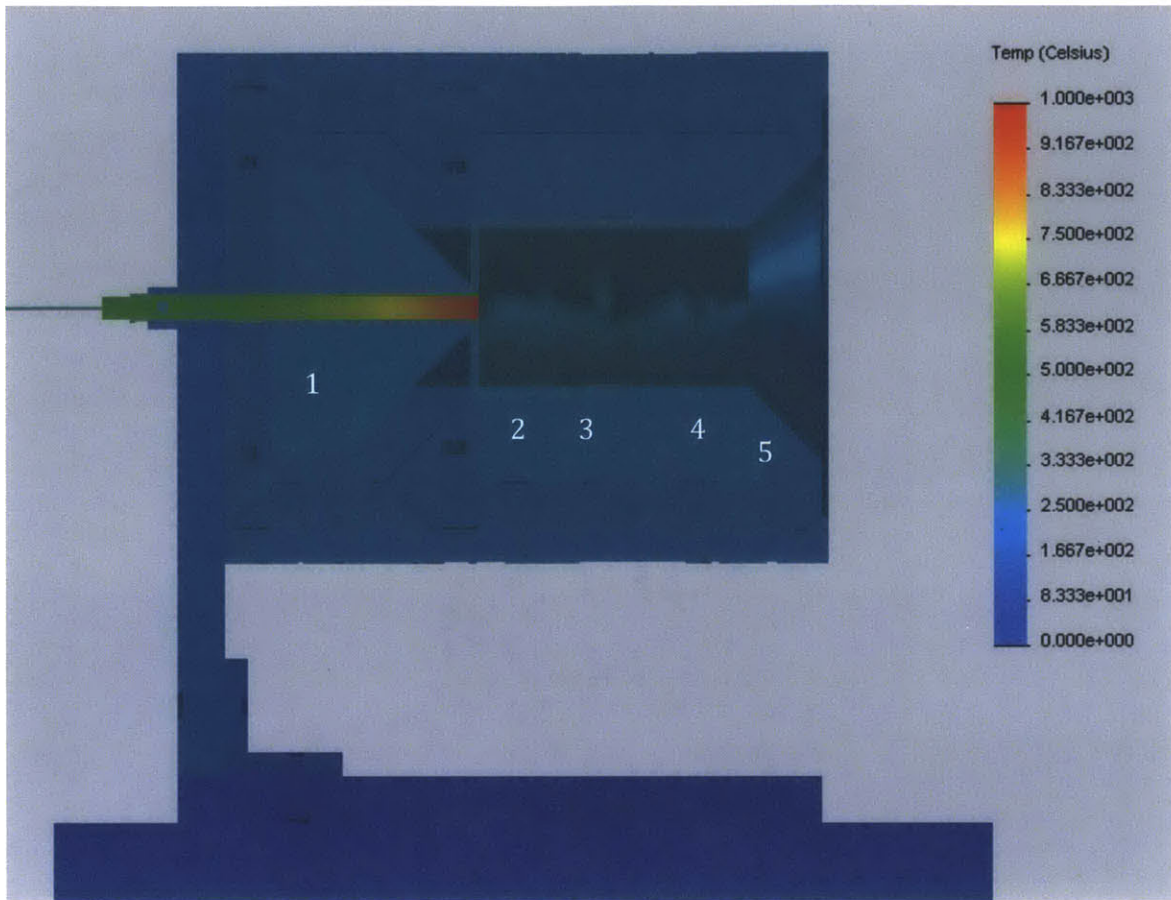


Figure 8: Thermal interior of the Cusped Field Thruster. Magnets are labeled in white.

Magnet	Average Temperature (°C)	Maximum Temperature (°C)
1	225	235
2	224	229
3	230	235
4	224	229
5	219	223

Table 2: Magnet temperature data from the thermal study.



The results of this thermal study showed that the magnets would not overheat. All points within the magnet remained at a temperature lower than the curie temperature of Samarian Cobalt Type 3212: 800°C. There is also a low thermal gradient within the magnets and all other parts of the thruster besides the anode stem.

Preliminary validation for this simulation can be found in recent thermal measurements taken from the original DCFT. An average temperature of roughly 300 degrees C was measured on the surface of the erosion shield. For CFT thermal simulation, an average temperature of 254 degrees C was predicted for the erosion shield surface.

### **3.4 Cathode**

The cathode designed to work with this thruster is identical to that of the original DCFT. It was designed and manufactured by the Busek Corporation. The hollow cathode emits electrons by pumping current through a wire with a low work function. Once sufficiently heated, additional current can be extracted via thermionic emission. This emission is enhanced by an electric field, which lowers the effective work function of the material.

Some of the electrons emitted from this cathode will make their way to the anode, ionizing the xenon atoms on their way there. The plasma acts as a bridge on which the electrons can travel. After the xenon ions leave the thruster, is essential that this particles stream be neutralized to prevent them from returning to the thruster due to an accumulating charge. Therefore, the

cathode must provide an additional electron current equal in magnitude to the beam current to neutralize the beam.

### 3.5 Anode



Figure 9: CAD drawing of the anode.

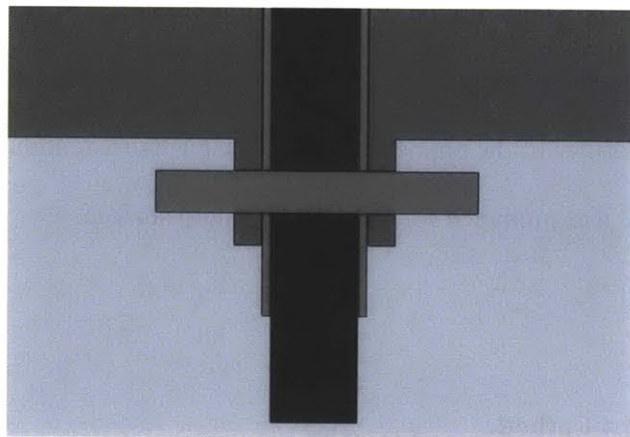


Figure 10: CAD drawing of the anode, anode sheath, stand base, and pin.

This thruster uses a cylindrical anode made of graphite. Graphite was selected because of its low sputter yield and higher melting point compared to more conventional materials. It is also a good electrical conductor. The anode is 5mm in diameter, identical to that of the original thruster. It is electrically insulated from the rest of the thruster by the anode sheath (no plasma connotation): a 0.5mm thick concentric boron nitride tube. The anode is secured to the thruster by a ceramic pin: a 2.5 mm hole is drilled through the anode, the anode sheath, and the aluminum back plate of the thruster. The pin is then inserted. A clip can be used to connect the anode to an electrical source. If at some future time it would benefit experimenters to have the anode protrude into the

chamber, a longer anode can be easily substituted. This anode will typically operate at a potential difference of 300 V, providing approximately 250 W of power.

### 3.6 Erosion Shielding

An erosion shield was carefully designed to protect the parts of the thruster that could be eroded due to ion bombardment. Erosion will take place inside the chamber and at the top of the thruster, both of which the shield covers. However, experiments from the DCFT show that the erosion will be concentrated most heavily at the cusps.<sup>1</sup>

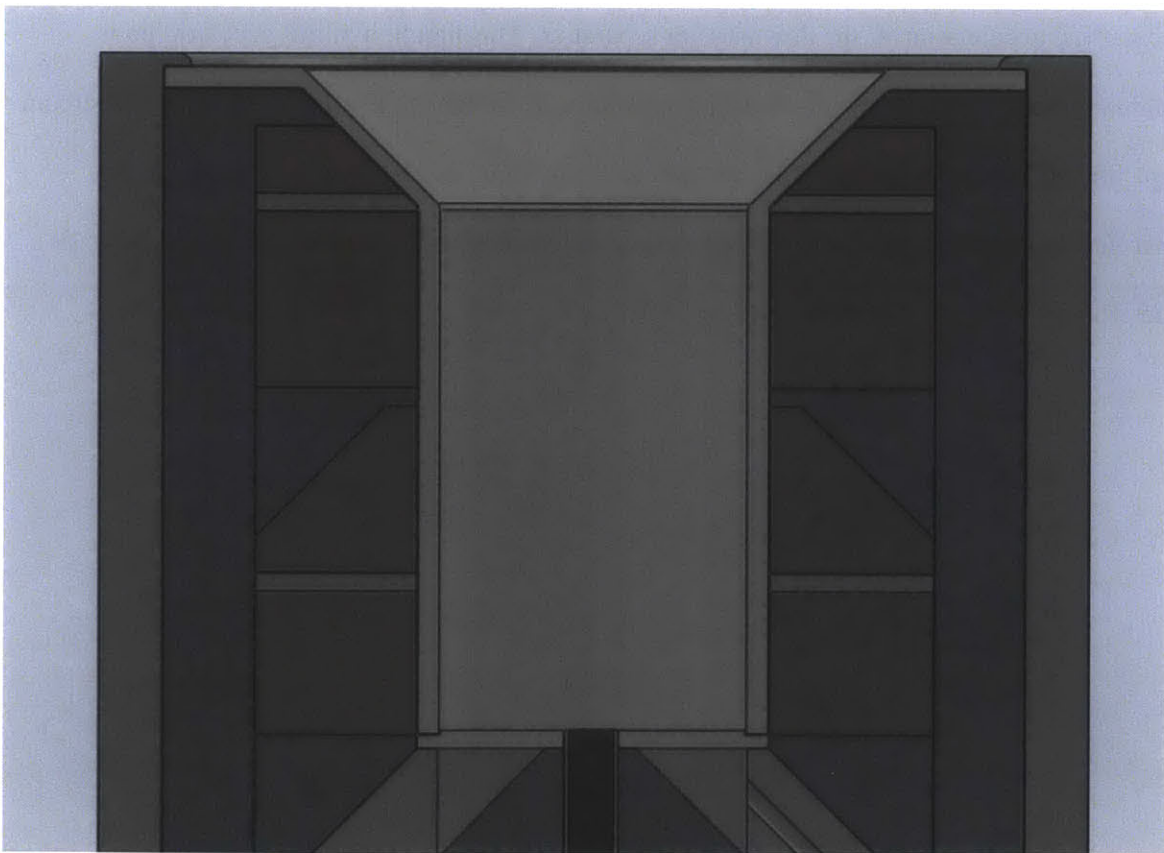


Figure 11: CAD drawing of the erosion shield and surrounding parts.

The thickness of the erosion shield is identical to that of the original thruster: 2.5 mm. This has been shown to provide adequate longevity and is also machinable. Fillets are used on the chamfer to avoid stress concentrations. The shield abuts 0.5 mm into the diffuser disk to avoid a gap forming due to thermal expansion. It is held in place by the outer aluminum casing, which is connected to the stand by six screws. To access the erosion shield, all that is necessary is to remove the six screws and to remove the outer aluminum casing.

Another important feature of the erosion shield is the position at which the chamfer begins. This was designed in tandem with the steel and magnet configuration. It is believed that ions undergo the highest acceleration at the downstream separatrix. The direction of this acceleration is approximately normal to the plane of the separatrix. Even though the thruster has a downstream separatrix that is perpendicular to the chamber walls, some dispersion may still occur. The chamfer begins at the downstream separatrix to avoid stray ions from colliding with the walls and eroding it.

### 3.7 Gas Diffusion System

To supply xenon gas to the thruster, a gas supply can be connected to the gas line. This gas line penetrates the stand base, the circuit base, and part of the gas transporter.

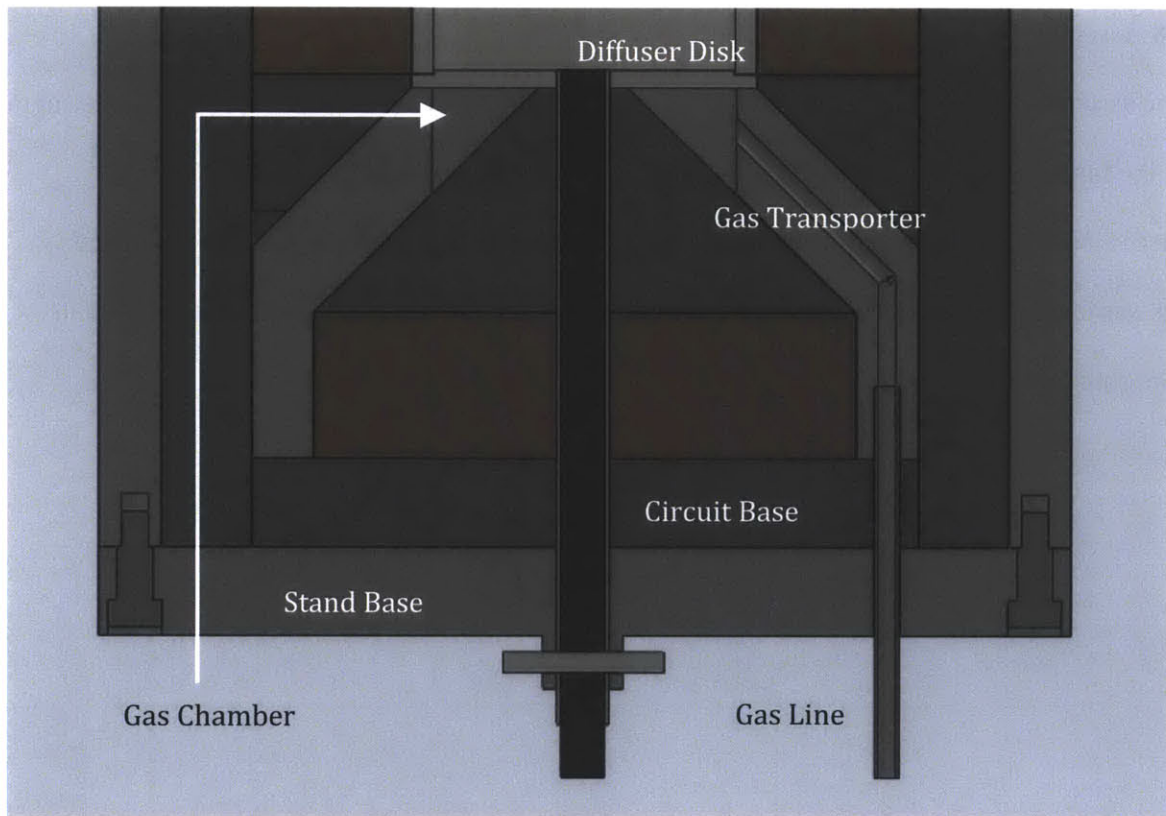


Figure 12: CAD Drawing of the gas diffusion system.

The gas transporter has the function of both a space holder and a gas pipeline. It has two joined holes to channel the gas to the gas chamber, where it is allowed to stagnate. It then passes through the porous ceramic gas diffuser disk and into the thruster. The gas diffuser is 2mm thick – approximately equal to that of the original thruster. Porous ceramic is advantageous because it can be machined without reducing the permeability. This system is designed to allow xenon to

flow uniformly into the thruster in a controlled manner. The flow rate will be approximately 10 sccm.

### **3.8 Assembly**

The assembly of the new cusped field thruster is a very involved process. Because of the strength of the samarium cobalt magnets, there are many difficulties that must be overcome to successfully move the magnets into place so that they may be secured by screws. An assembly rig was designed to accommodate this process. This rig has three configurations, each with its own set of steps.

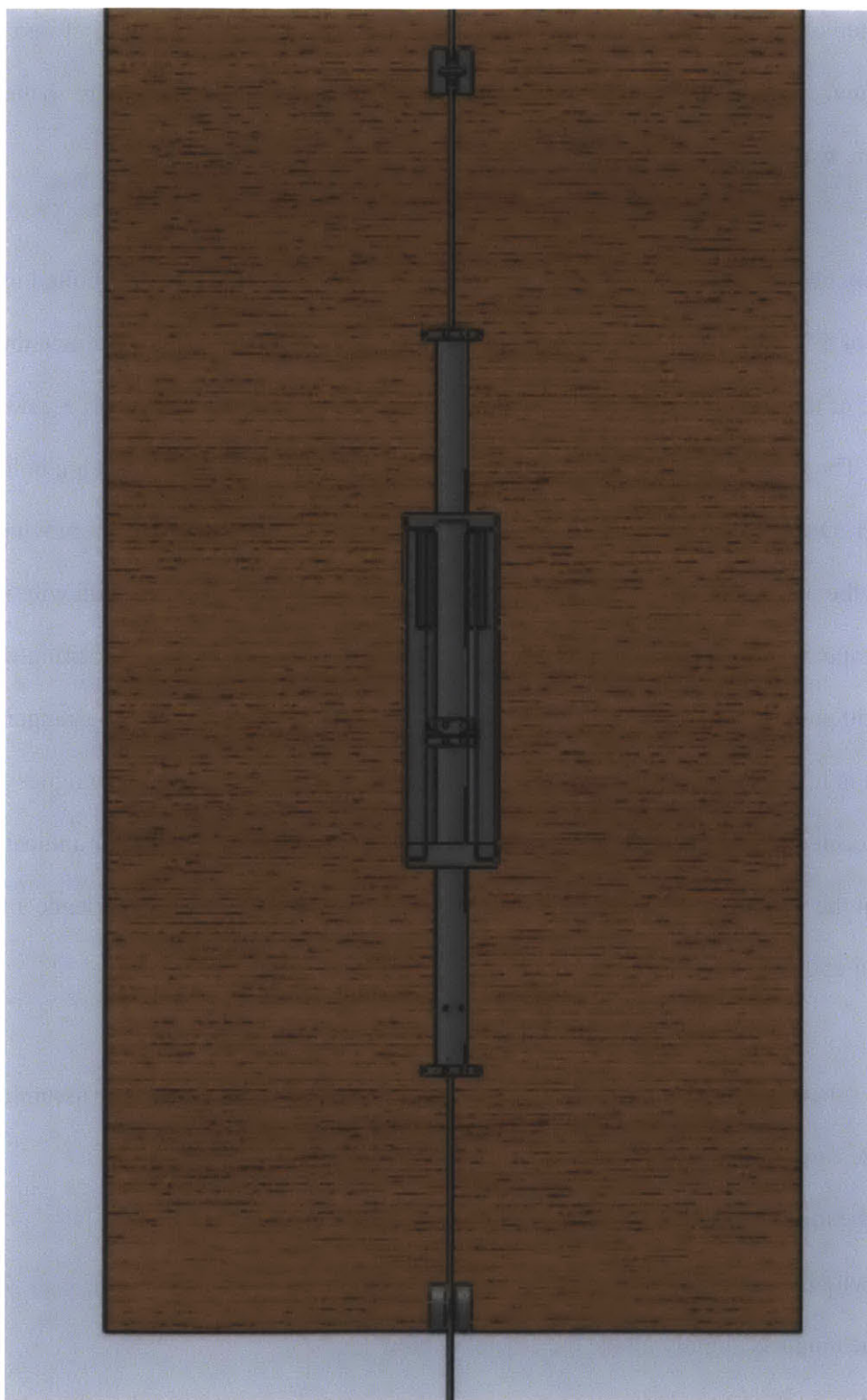


Figure 13: Assembly Rig, First Configuration.



This first step of the assembly process was designed to insert the uppermost magnet into the magnetic steel casing. Samarium cobalt magnets are extremely strong and prone to shattering, so extreme care was taken to fully constrain the part as it slides into place.

An assembly tube was designed to constrain the magnetic casing. This tube was bolted into a long sheet of 5/8 inch thick plywood. Inside the tube runs an assembly cylinder. Since the hole on one side of the assembly tube has a larger diameter than the assembly cylinder, a guiding ring is inserted. The magnet slides onto this cylinder and is constrained by braces that are bolted onto the cylinder. On each end, there are stops that prevent the assembly cylinder from moving so far as to crush the magnet. There are also eyehooks on each end that are threaded with wire rope. This wire rope runs through pulleys on each end. On one end there is a precise position winch rated for 750 pounds, and on the other side hangs a 150 pound weight. With this arrangement, the magnet is fully constrained. Since there is great tension in the wire rope, the magnet will not suddenly accelerate into the magnetic cylinder and shatter. A Maxwell simulation indicated that a magnet in the vicinity of the magnetic casing or other magnets will never experience a force greater than 150 pounds.

Here is the procedure to install the top magnet using the first configuration of the assembly rig:

- 1) Move the assembly cylinder into the back position
- 2) Secure the top magnet to the assembly cylinder using two braces
- 3) Put the wire rope under tension
- 4) Move the magnets slightly inside the assembly tube
- 5) Attach the guiding ring



- 6) Move the magnet all the way through the assembly tube until the stop contacts the guiding ring
- 7) Release the tension from the wire rope wire
- 8) Remove the front cover of the assembly tube
- 9) Remove front brace
- 10) Reattach front cover of the assembly tube
- 11) Pull assembly cylinder back most of the way
- 12) Remove the guiding ring
- 13) Move the back brace out of the assembly tube
- 14) Remove the back brace

After these steps are completed, the top magnet will have been fully inserted into the magnetic casing.

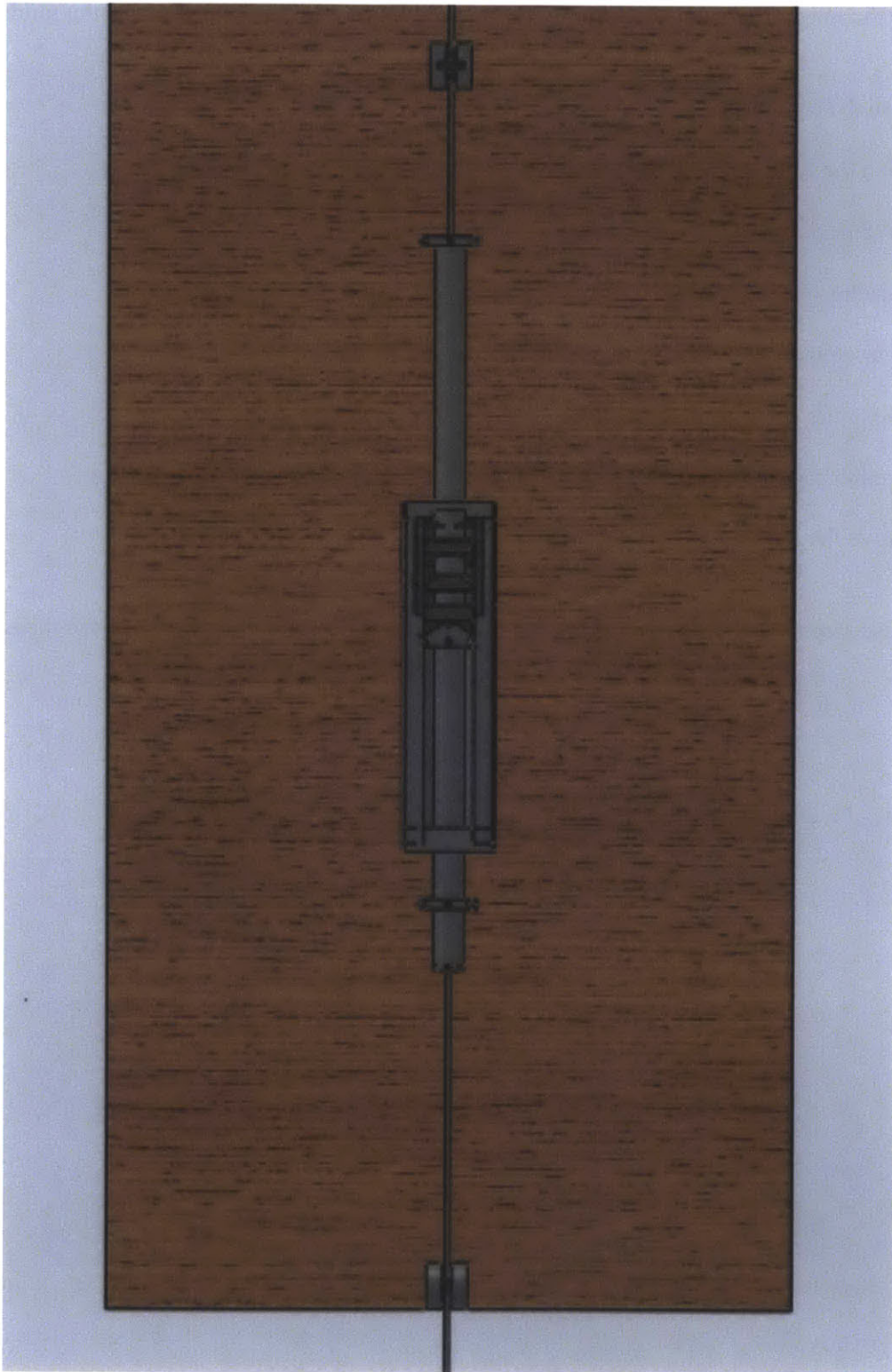


Figure 14: Assembly Rig, Second Configuration.

The second configuration of the assembly rig is designed to insert the next four magnets. It relies on the same principles as the first configuration, but minor changes have been made since each of these magnets will feel a repulsive force. Unlike the first magnet, which sticks to the magnet casing, these magnets must be held in place until screws are inserted through access holes in the assembly tube. It may be necessary to rotate the assembly cylinder to line up the holes. That is why there is a small notch on the brace and a small groove on the last part to be inserted. This will provide a motion similar to a lock and key.

Here is the procedure for the second configuration of the assembly rig:

- 1) Move the assembly cylinder into the back position
- 2) Slide the remaining four magnets and spacers into the assembly tube. It is important that some of the magnets be already attached to the steel parts (as seen in figure 14)
- 3) Attach the brace
- 4) Put the wire rope under tension
- 5) Move the brace into the assembly tube
- 6) Attach the guiding ring
- 7) Move the assembly cylinder through the assembly tube until the stop contacts the guiding ring
- 8) Rotate the assembly cylinder until the screw holes line up
- 9) Attach the screws
- 10) Release the tension from the wire rope
- 11) Pull assembly cylinder back most of the way
- 12) Remove the guiding ring

13) Move the brace out of the assembly tube

14) Remove the brace

After these steps are completed, four magnets are secured inside the magnet casing.

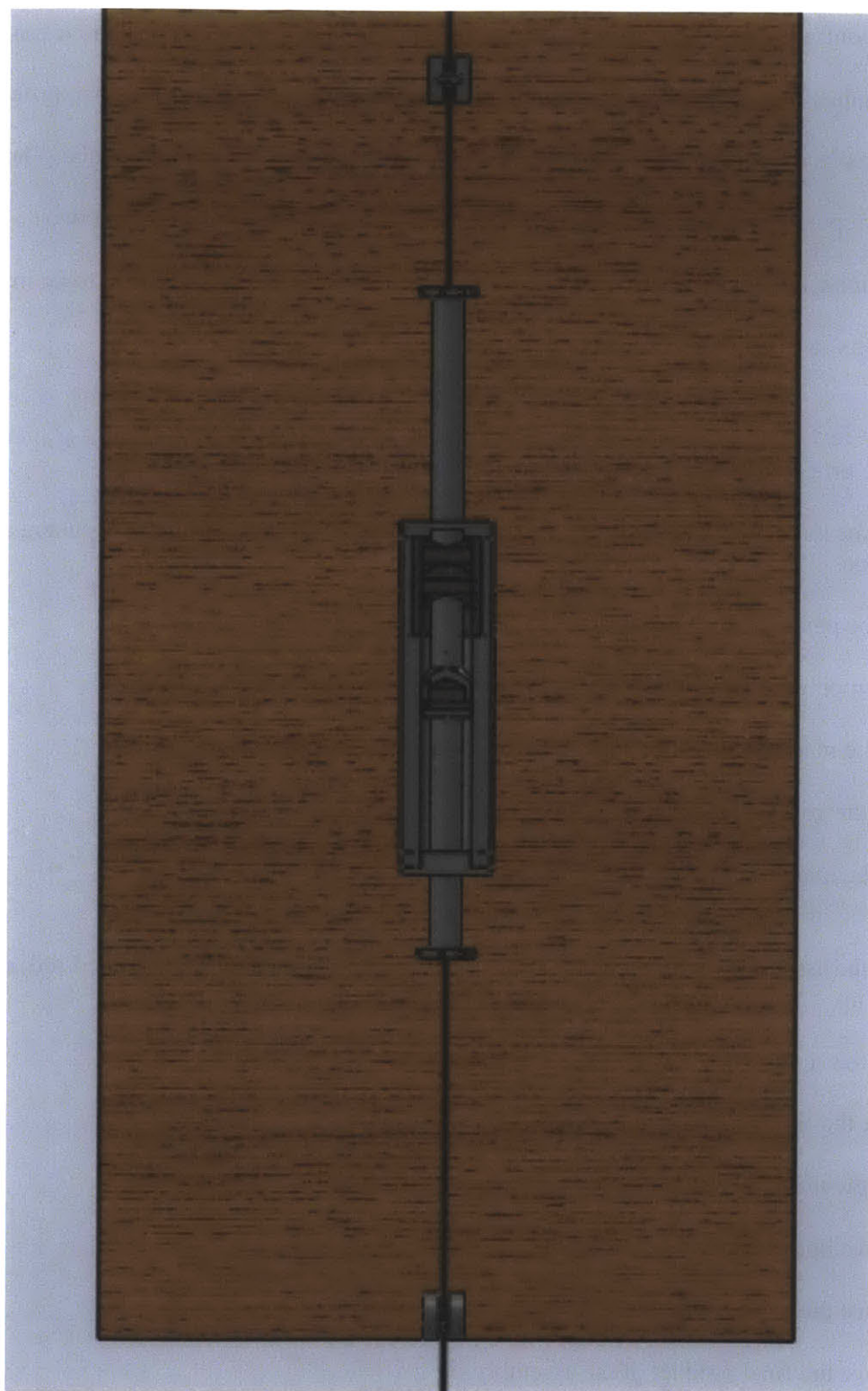


Figure 15: Assembly Rig, Third Configuration.

The third configuration of the assembly rig is designed to insert and secure the anode magnet and the surrounding parts. They will be inserted in the same manner as the previous two procedures and held in place until screws are inserted through access holes in the assembly tube. The magnet will feel a repulsive force from the other magnets as it is inserted. Unlike the first two configurations, no braces are used. Instead, a threaded rod runs through the parts to be inserted and connects to two smaller assembly cylinders.

Here is the procedure for the third configuration of the assembly rig:

- 1) Attach the magnet and surrounding parts to the two smaller assembly cylinders using a threaded rod
- 2) Insert the parts and the assembly cylinder into the assembly tube
- 3) Put the rope wire under tension
- 4) Move the magnets slightly inside the assembly tube
- 5) Attach the guiding ring
- 6) Move the magnets through the assembly tube until the stop contacts the guiding ring
- 7) Rotate the assembly cylinders the (correct way that does not loosen the threaded rod) until the holes line up
- 8) Attach the screws
- 9) Release the tension from the wire rope
- 10) Unscrew the assembly cylinders
- 11) Remove both assembly cylinders
- 12) Remove the front cover of the assembly tube
- 13) Remove the final product of the assembly rig

After these steps have been completed, the difficult parts of the assembly have been completed.

All other parts to be added will not be subjected to magnetic forces.

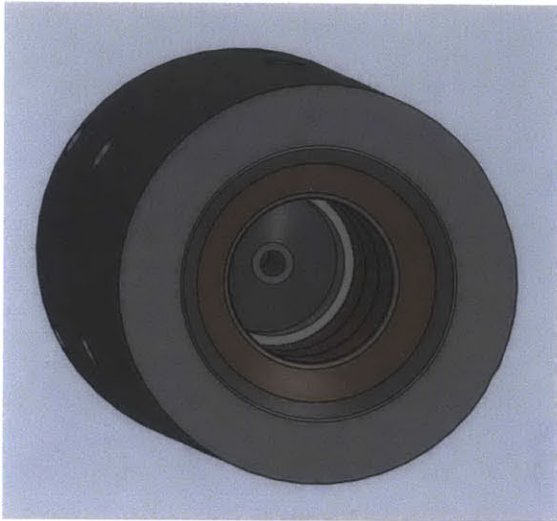


Figure 16: Final product of the assembly rig.

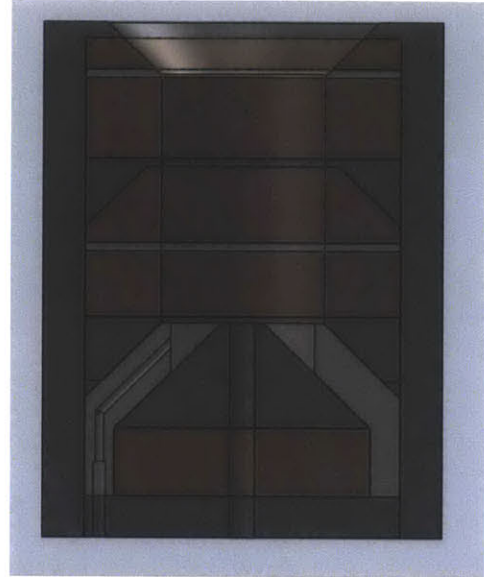


Figure 17: Cutaway view of the final product of the assembly rig.

After the magnet case has been filled, there remain some additional steps to successfully assemble the thruster. Here are the steps in order:

- 1) Weld the gas line to the gas transporter
- 2) Insert the diffuser disk
- 3) Insert the erosion shield
- 4) Cover the thruster with the outer aluminum case
- 5) Assemble and attach the stand
- 6) Insert the anode and anode sheath
- 7) Insert the pin



After these steps have been completed, the thruster has been fully assembled.

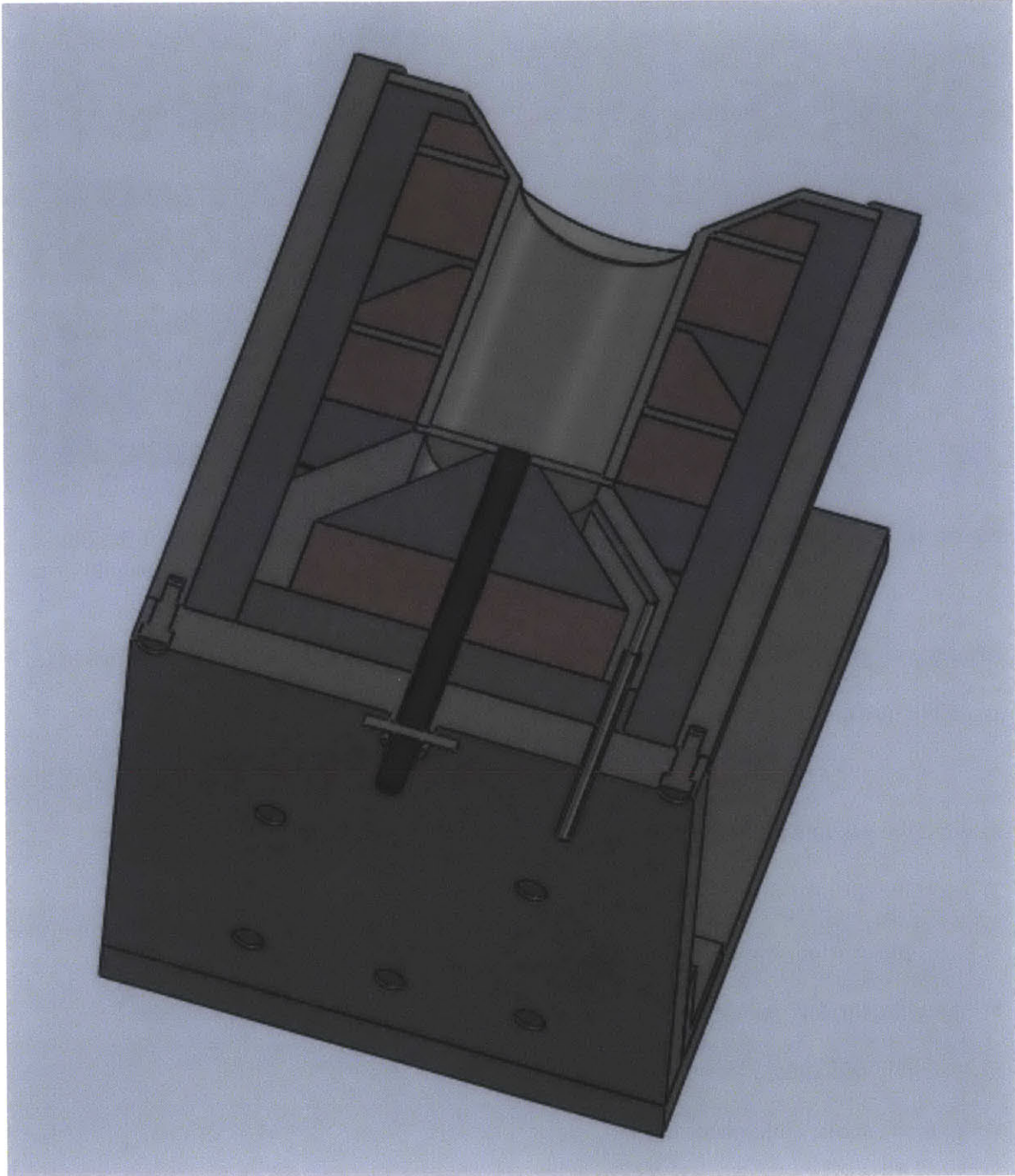


Figure 18: Cutaway CAD drawing of the fully assembled thruster.



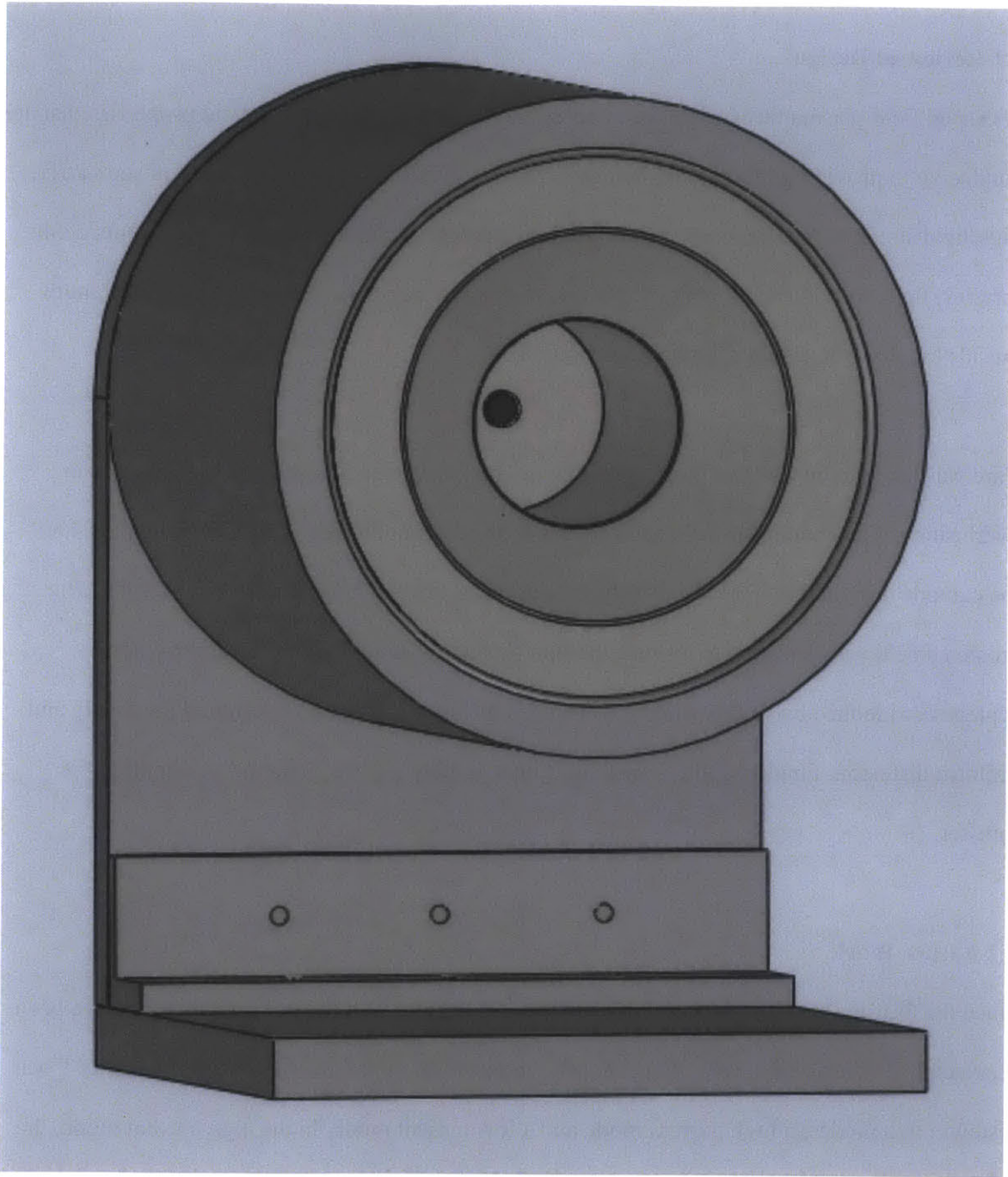


Figure 19: CAD drawing of the fully assembled thruster.

# Conclusions

## 4.1 Review of Design

A cusped field plasma thruster has been designed. It has several magnetic field properties that are conducive to providing increased thrust and efficiency, including a flat downstream separatrix, high field strength near the cusps, and high field strength and gradient at the anode. Outside the thruster, field lines allow for cathode placement outside the plume, however the field strength outside the thruster mouth is higher than optimal.

Care was taken to ensure that the magnets do not become demagnetized due to proximity or overheating. The anode was designed for easy replacement of anodes of different lengths, and the cathode designed to work for this thruster was identical to that of the original DCFT. The erosion shield was designed to provide erosion protection and is chamfered at the outer separatrix to reduce collisions with ions. The gas diffusion system was designed for steady and uniform diffusion. Finally, a three-configuration assembly rig was designed to assemble the thruster.

## 4.2 Future Work

Once the thruster has been successfully constructed, testing is in order. Previous tests have been conducted to measure ion velocity using laser induced fluorescent measurements. The DCFT was tested in two modes: a high current mode and a low current mode. In the high current mode, the anode discharge current oscillates. It would be interesting to see if the DCF is more stable at high currents. Plume shape is also important to measure. The DCFT had a divergent plume, while the DCF should have a more focused plume. Another factor is plume color. A purple plume is

indicative of poor ionization, while a blue plume is indicative of good ionization. Finally, the performance of the DCF can be measured against its predecessor. Operating at 242W of anode power and 8.5sccm of propellant, the DCFT was able to attain a specific impulse of 1640 s. A maximum thrust of 16mN was attained while operating at an anode voltage of 400V and a xenon flow rate of 10.0 sccm. It is hoped that the Cusped Field Thruster will be able to exceed these measurements.

# Bibliography

<sup>1</sup>Courtney, D., *Development and Characterization of a Diverging Cusped Field Thruster and a Lanthanum Hexaboride Hollow Cathode*, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, June 2008.

<sup>2</sup>Matlock, T., Fuzhou, H., and Martinez-Sanchez, M., *Controlling Plume Divergence in a Cusped-Field Thruster*, 32<sup>nd</sup> International Electric Propulsion Conference, Wiesbaden, Germany, September 2007, also IEPC-2011-178.

<sup>3</sup>McDonald, N., Cappelli, M., Gildea, S., Martinez-Sanchez, M., Hargus, W., *Laser-Induced Fluorescence Velocity Measurements of a Diverging Cusped Field Thruster*, American Institute of Aeronautics and Astronautics.

<sup>4</sup>Matlock, T., Gildea, S., Hu, F., Becker, N., Lozano, P., Martinez-Sanchez, M., *Magnetic Field Effects on the Plume of a Diverging Cusped-Field Thruster*, American Institute of Aeronautics and Astronautics.

<sup>5</sup>D. M. and Katz, I., *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, JPL Space and Technology Series, John Wiley & Sons, 2008.

<sup>6</sup>Nishino, K., Yamashita, S., Torii, K., *Thermal Contact Conductance Under Low Applied Load in a Vacuum Environment*, Experimental Thermal and Fluid Science, Volume 10, Issue 2, February 1999.

<sup>7</sup>Saint-Gobain Boron Nitride, *HP Grade Boron Nitride*, [www.bn.saint-gobain.com](http://www.bn.saint-gobain.com).

<sup>8</sup>Dexter Magnetic Technologies, *Samarium Cobalt (Sm-Co) Magnets*, <http://www.dextermag.com/Samarium-Cobalt.aspx>.

<sup>9</sup>Poco Graphite, *AXF-5Q Grade Graphite*, [www.poco.com](http://www.poco.com).

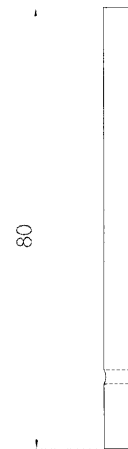
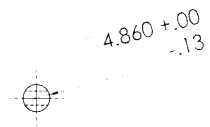
<sup>10</sup>Matweb Material Property Data, [www.matweb.com](http://www.matweb.com).

<sup>11</sup>*Handbook of Chemistry and Physics, 92<sup>nd</sup> Addition*, <http://www.hbcpnetbase.com>.

<sup>12</sup> Cappelli, M., *Advanced Plasma Propulsion*, Stanford University.

## Appendix A

# **MIT Cusped Field Thruster Drawings**



2.500 THRU. +.13  
-.00

**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

MATERIAL: Graphite

FILE  
DATE

Anode

DESIGNED

Part1

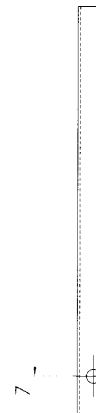
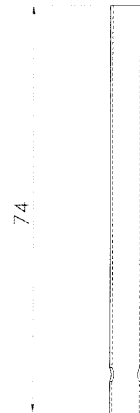
SUP  
A 1

SCALE

SHEET 1 OF 1

5 THRU.  $+0.13$   
 $-0.00$

5.860  $+0.00$   
 $-0.13$



**SolidWorks Student Edition.  
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Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions  
 unless otherwise specified.

MATERIAL: Boron Nitride

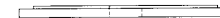
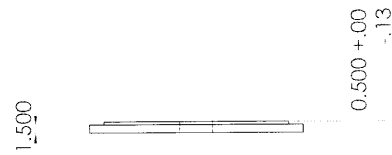
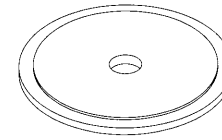
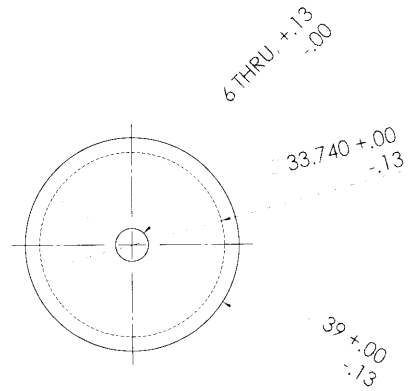
TITLE  
 DATE

Anode Sheath

DRAWN: Part2 User: A

SCALE: SHEET 1 OF 1





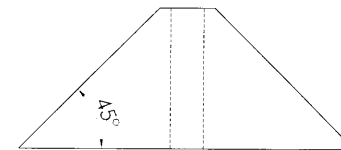
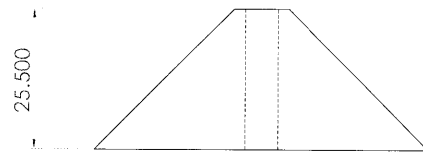
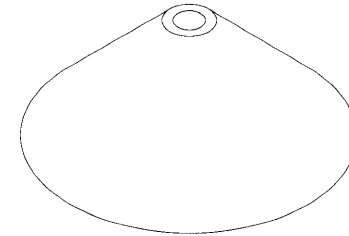
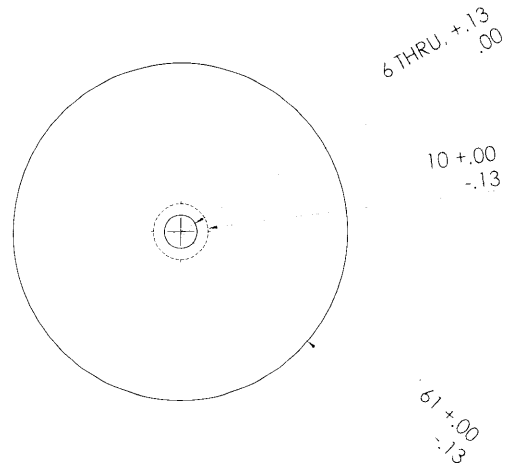
**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions, unless otherwise specified.

MATERIAL: Porous Boron Nitride

TITLE: Diffuser Disk

DESIGN: Part3 Size: A Rev: 1  
SCALE: SHEET 1 OF 1



**SolidWorks Student Edition.  
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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

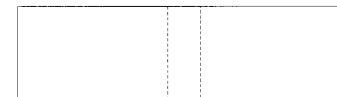
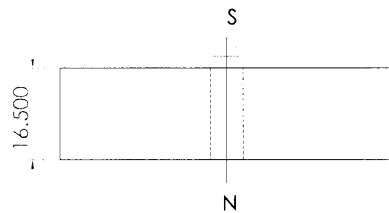
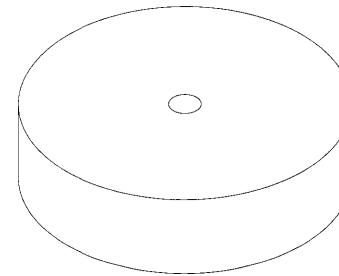
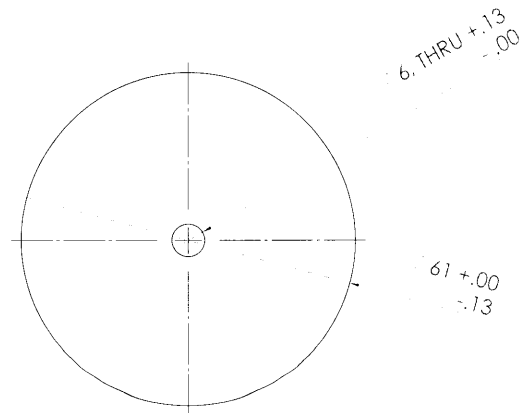
MATERIAL: 1018 Steel

TITLE: Field Focuser

DATE:

DWG NO: Part4

SCALE: SHEET 1 OF 1



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

MATERIAL: SmCo Type 3212

FILE  
DATE:

Magnet 1

DWG NO.

Part5

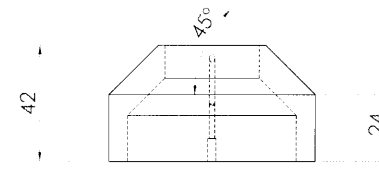
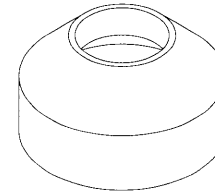
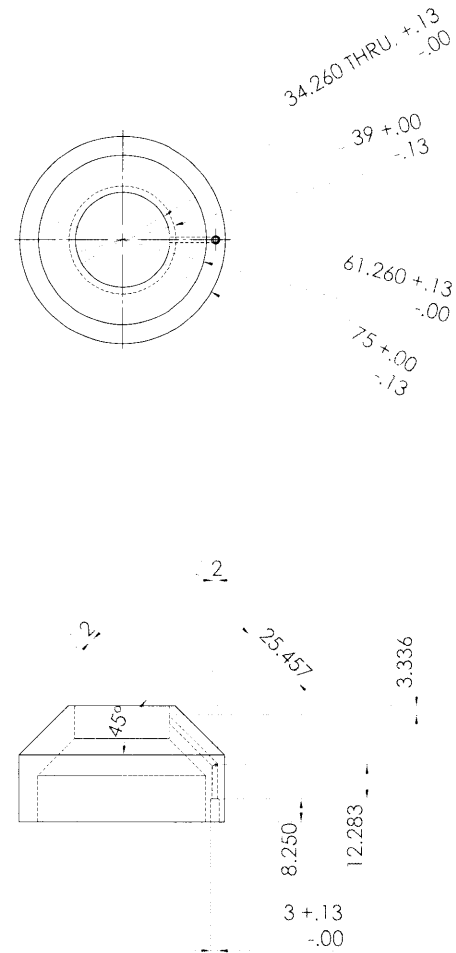
SUB  
A

REV  
1

SCALE

SHEET 1 OF 1

Note: The two holes in this part  
(one angled 45 degrees, one vertical)  
should connect within the part.



Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions,  
unless otherwise specified

MATERIAL: Aluminium

FILE  
DATE

Gas Transporter

DRAWING

Part6

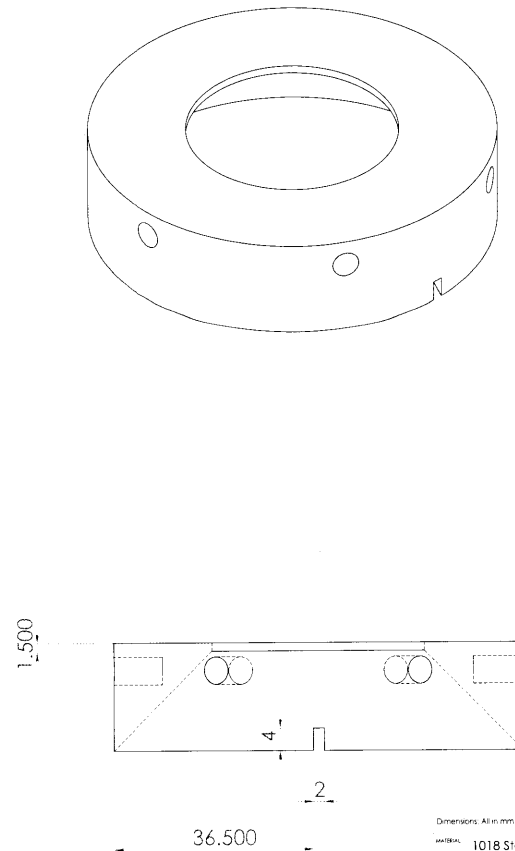
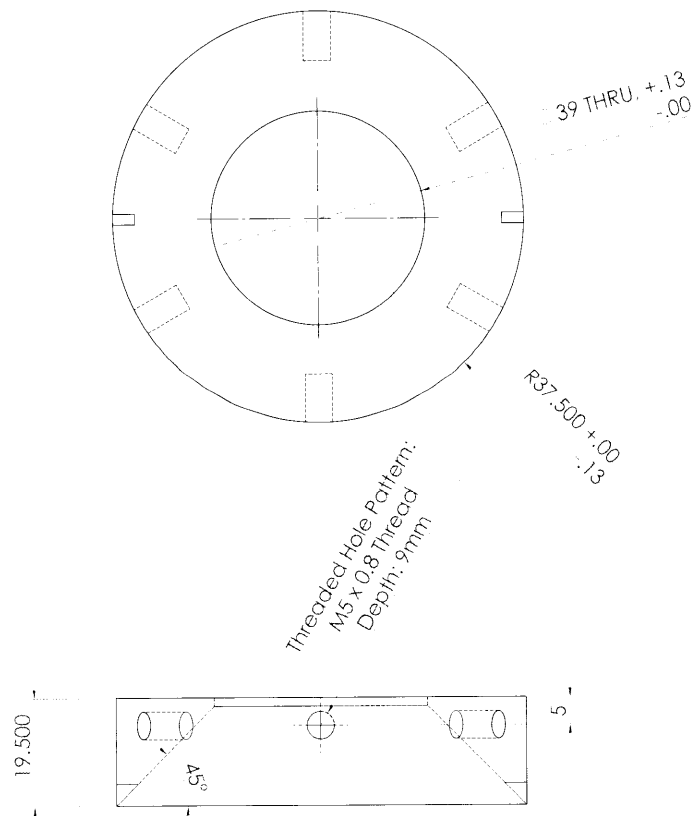
Size  
A

Rev  
1

SCALE

SHEET 1 OF 1

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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: 1018 Steel

TITLE

Field Diverter

DWG NO.

Part7

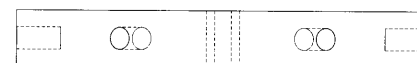
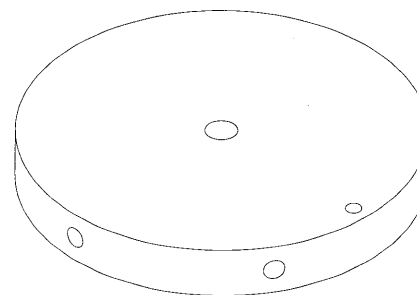
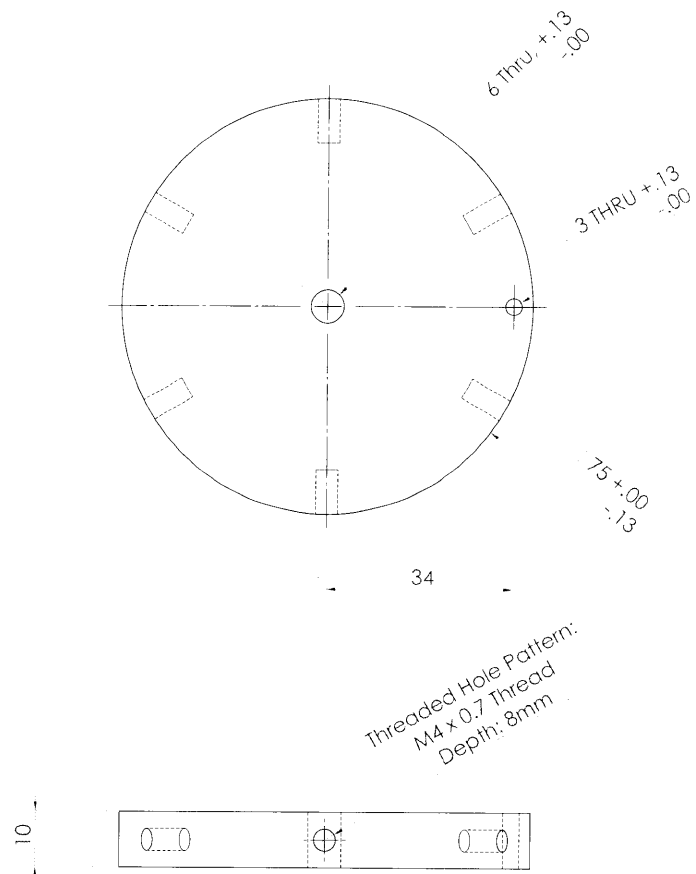
SUP A

REV 1

SCALE

SHEET 1 OF 1

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Dimensions: All in mm Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

MATERIAL: 1018 Steel

YRS  
DATE

Circuit Base

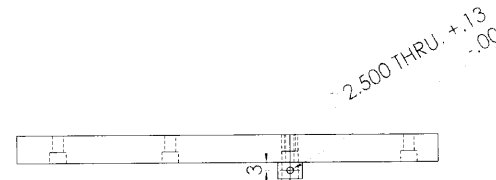
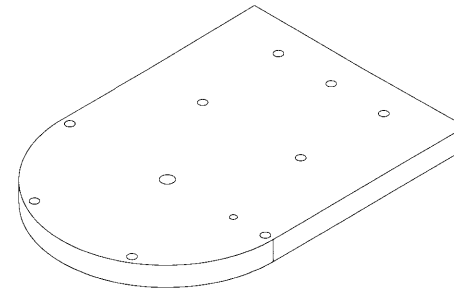
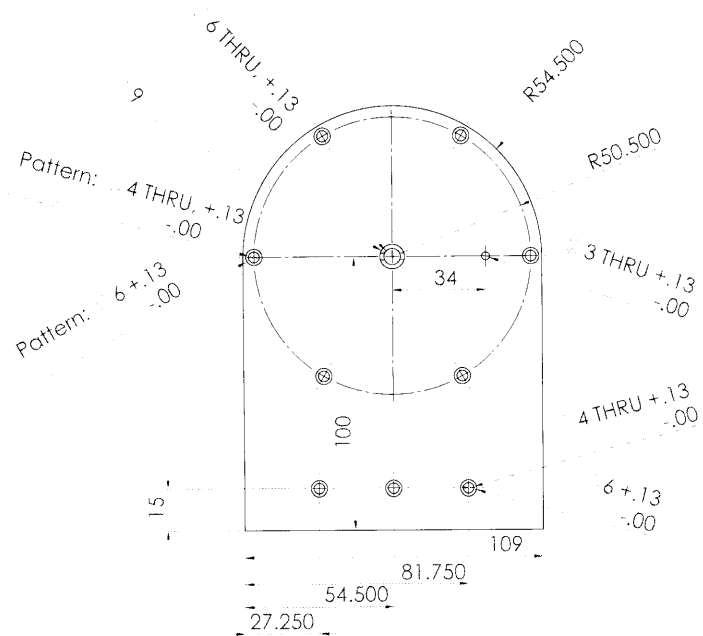
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Part8

Rev

SCALE

SHEET 1 OF 1



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Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions unless otherwise specified.

MATERIAL: Aluminium

TITLE

Stand Base

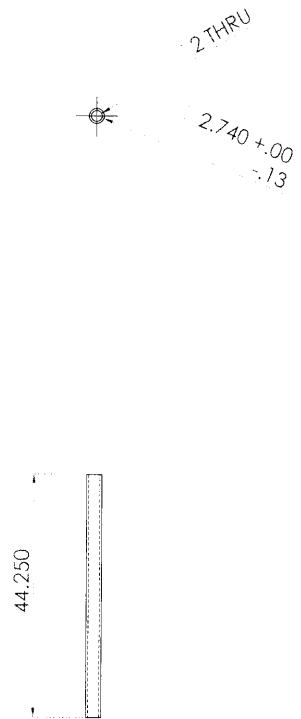
DWG NO.

Part10

Rev. 1

SCALE

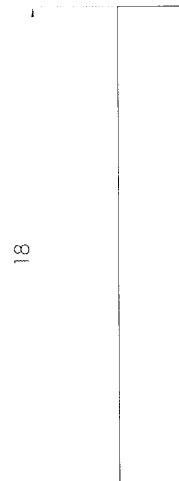
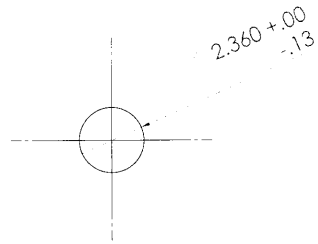
SHEET 1 OF 1



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Dimensions: All in mm		Tolerances: $\pm 0.13$ mm for all dimensions, unless otherwise specified	
MATERIAL	Aluminium		
TITLE	Gas Line		
DATE			
DWG NO	Part11	Size	Rev
SCALE	SHEET 1 OF 1		A I





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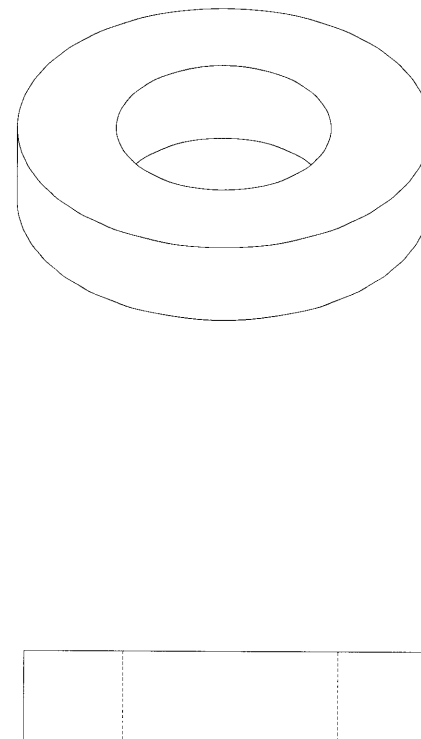
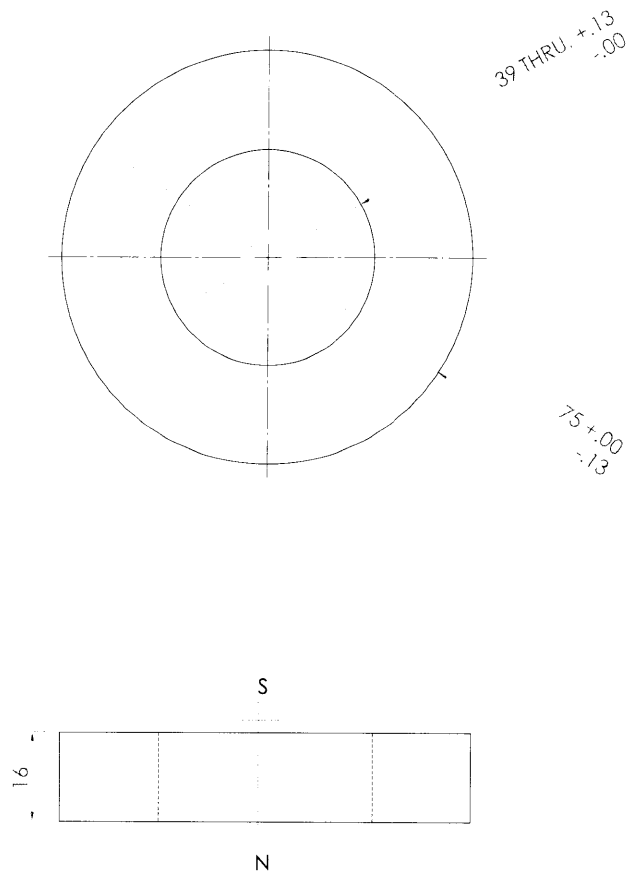
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MATERIAL: Boron Nitride

FILE  
DATE

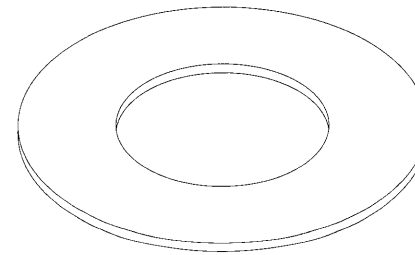
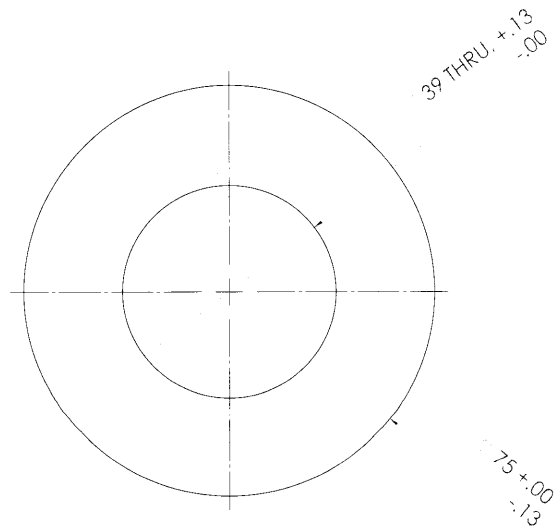
Pin

DRAWN: Part12 Size: A Rev: 1  
SCALE: SHEET 1 OF 1



**SolidWorks Student Edition.  
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 MATERIAL: SmCo Type 3212  
 TITLE: Magnet 2  
 DWG NO: Part13  
 SCALE: 1:1  
 SHEET 1 OF 1



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

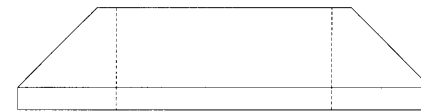
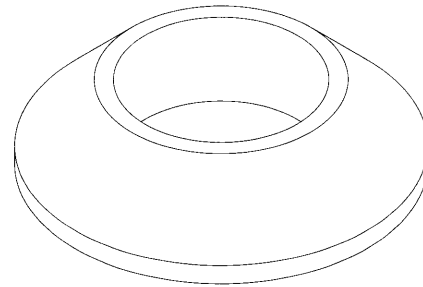
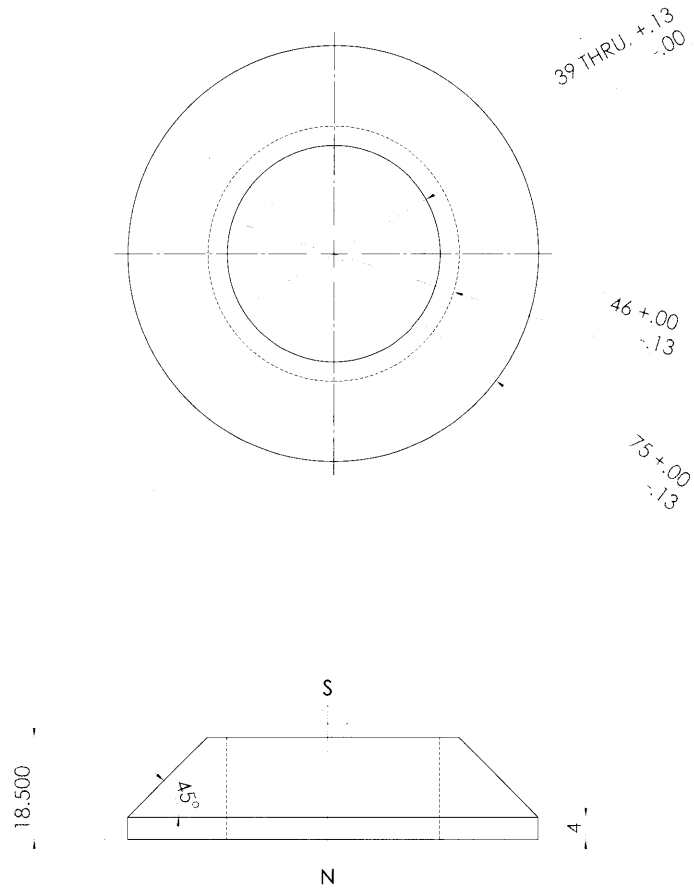
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TITLE: Flat Spacer

DWG NO: Part14

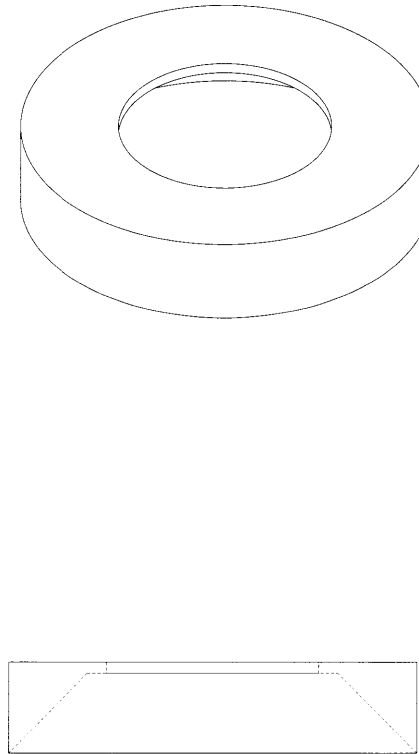
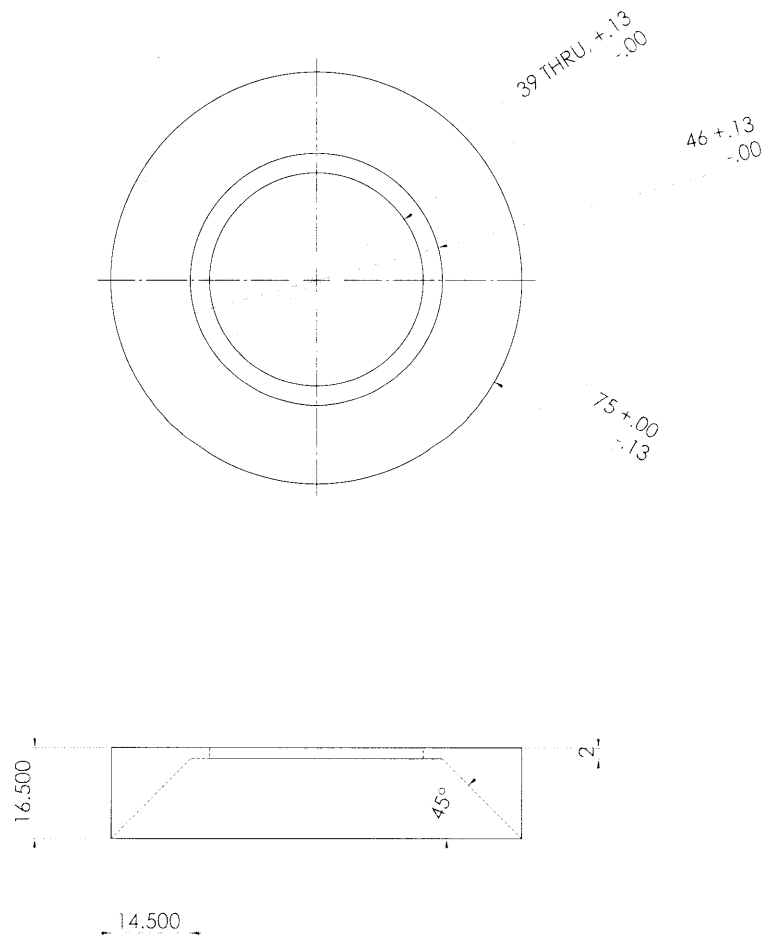
SCALE: 1:1

SHEET 1 OF 1



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.	
MATERIAL:	SmCo Type 3212
FILE	
DATE	
Magnet 3	
(DWG NO)	Part15
SCALE	SHEET 1 OF 1



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

MATERIAL: 1018 Steel

TITLE: CAT

Middle Spacer

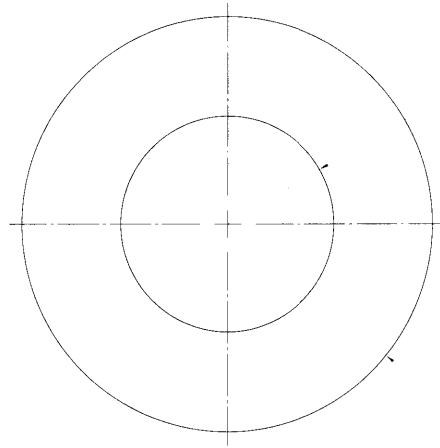
DESIGNER:

Part16

Rev. A

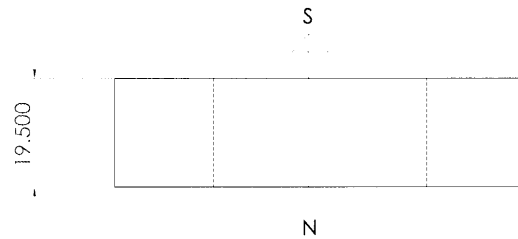
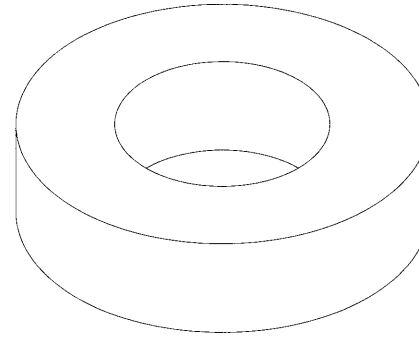
SCALE:

SHEET 1 OF 1



39 THRU, +.13  
-.00

75 +.00  
-.13



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Dimensions: All in mm Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

MATERIAL: SmCo Type 3212

FILE  
DATE

**Magnet 4**

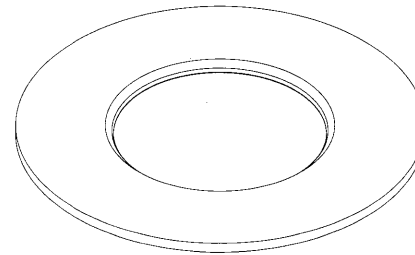
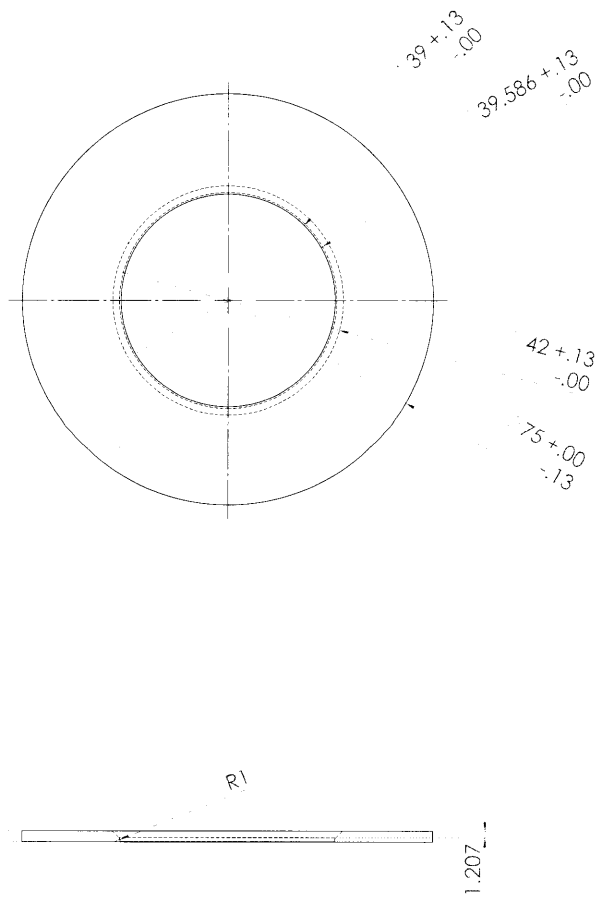
DWG NO

**Part17**

Size Rev  
A 1

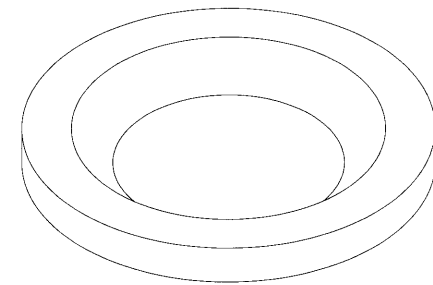
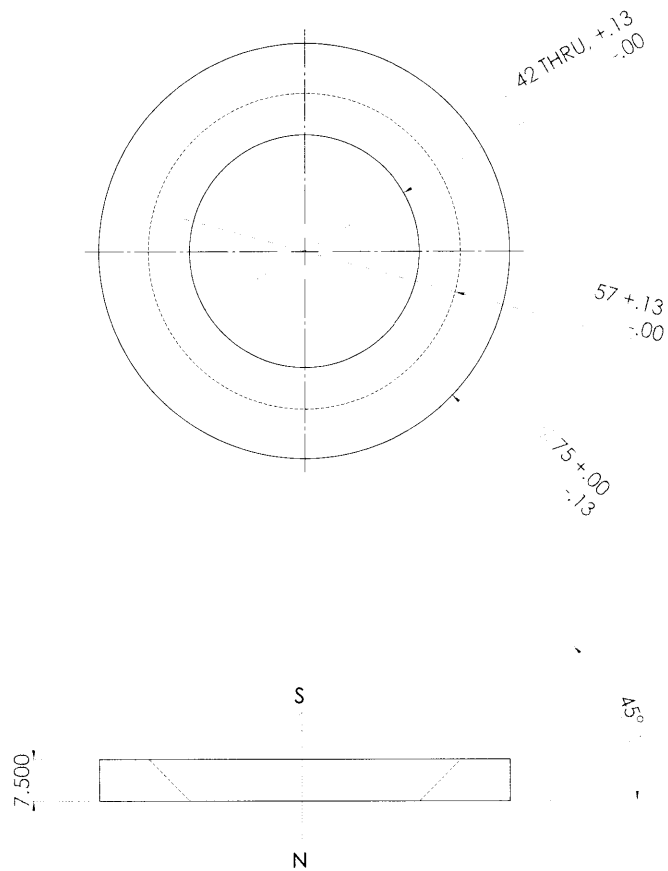
SCALE

SHEET 1 OF 1



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Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions unless otherwise specified  
 MATERIAL: Aluminium  
 TITLE: Angled Spacer  
 DESIGNED: Part18  
 SCALE: 1:1  
 SHEET 1 OF 1



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Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions.  
Unless otherwise specified.

MATERIAL SmCo Type 3212

TITLE

DATE

Magnet 5

DWGNO

Part19

Size

A

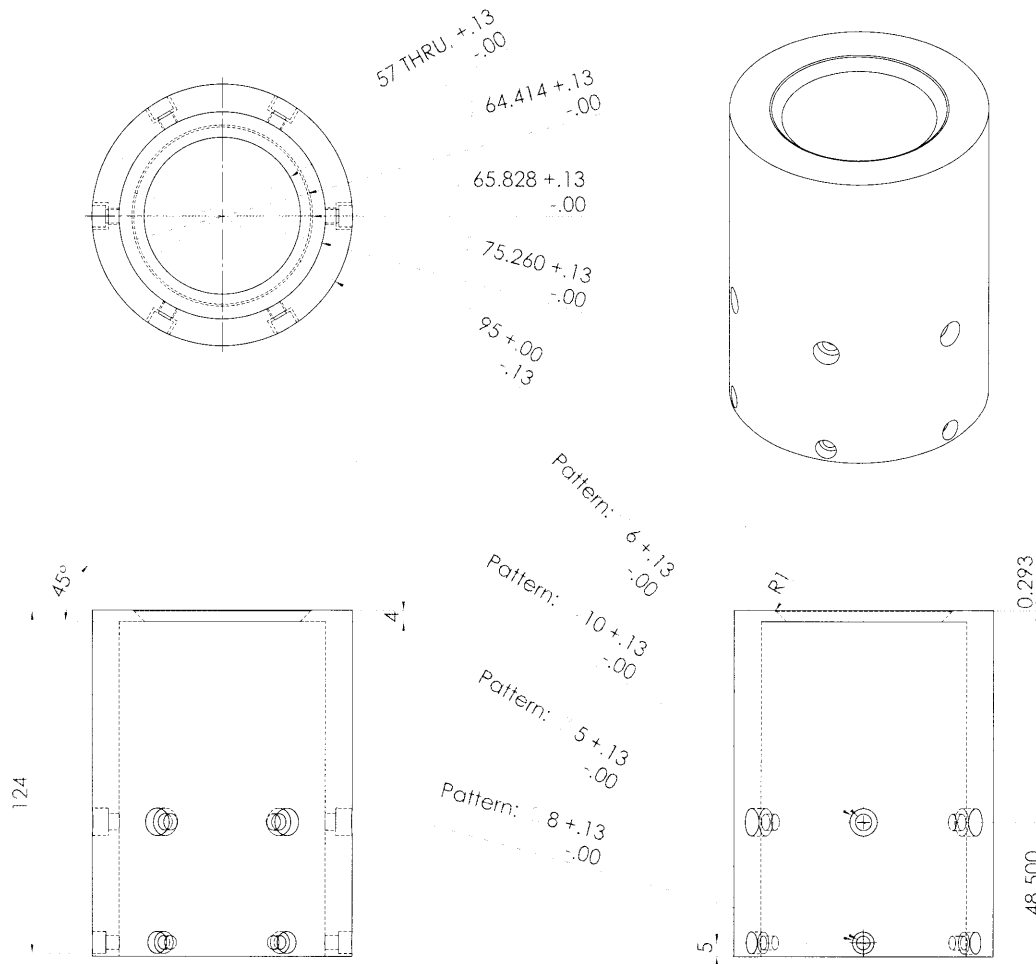
Rev

1

SCALE

SHEET 1 OF 1





**SolidWorks Student Edition.  
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Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions, unless otherwise specified.

MATERIAL 1018 Steel

TITLE DATE

Magnet Casing

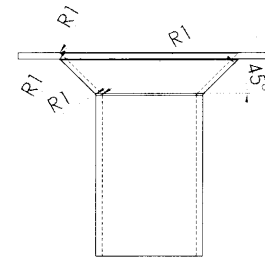
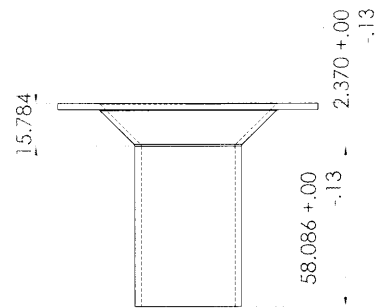
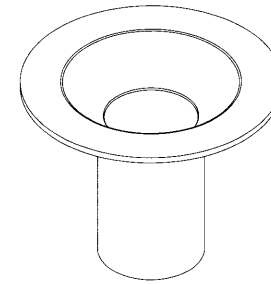
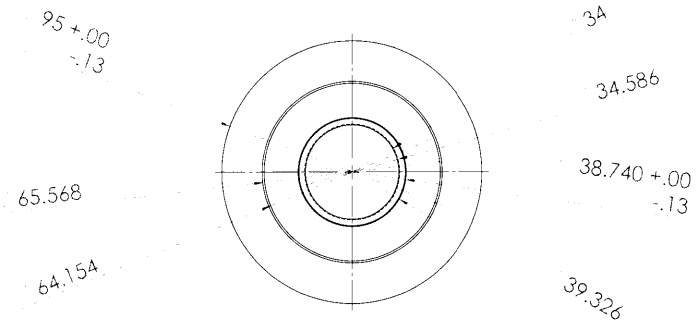
DWG NO.

Part20

SHEET 1 OF 1

SCALE

SHEET 1 OF 1



**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions  
unless otherwise specified

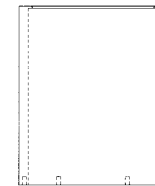
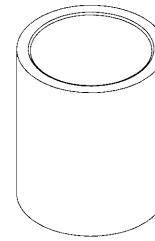
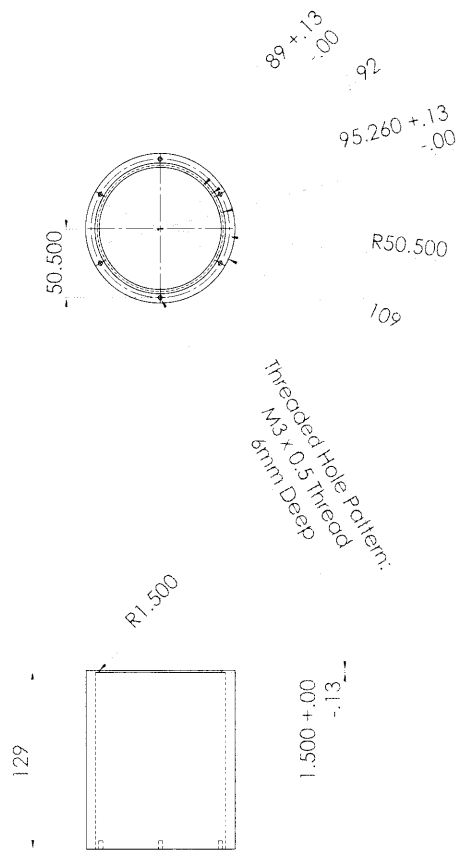
WATSON Boron Nitride

FILE  
DATE

INSULATOR Cone

DESIGN NO. Part21 Size A Rev. I

SHEET 1 OF 1



**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm Tolerances: 0.13 mm for all dimensions, unless otherwise specified

MATERIAL Aluminium

REV DATE

Outer Case

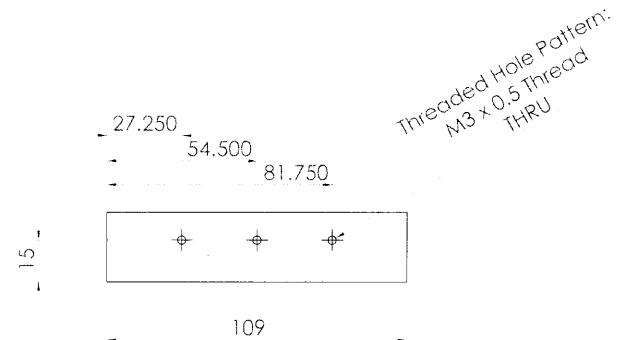
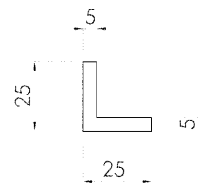
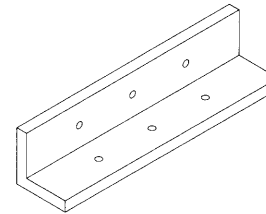
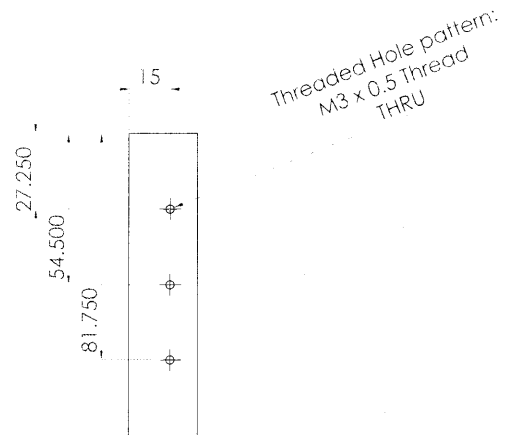
DESIGN

Part22

VER A Rev 1

SCALE

SHEET 1 OF 1



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Dimensions: All in mm Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

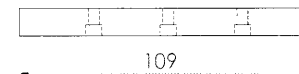
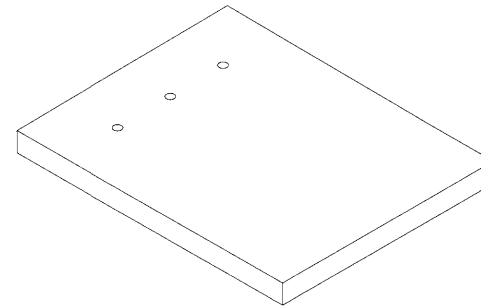
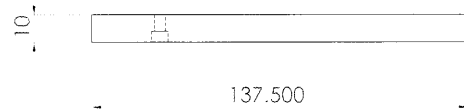
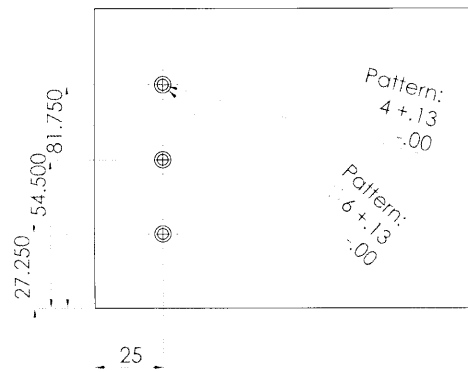
MATERIAL: Aluminium

FILE  
DATE

Stand Elbow

DWG NO: Part23 Size: A Plot: 1

SCALE: 1:1 SHEET 1 OF 1



Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions unless otherwise specified

MATERIAL: Aluminium

TITLE  
DATE

Base Plate

DRAWN

Part24

SUP  
A

REV  
1

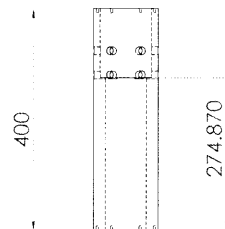
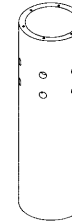
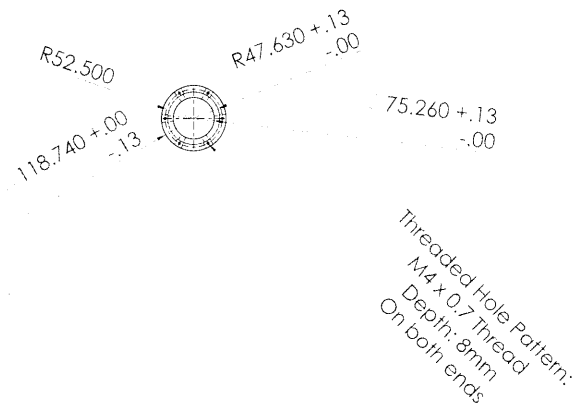
SCALE

SHEET 1 OF 1

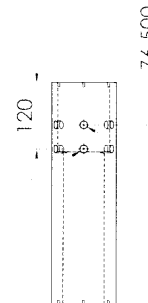
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# Assembly Rig Drawing

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Pattern:  
14 THRU.  $+0.13 -0.00$



Pattern:  
14 THRU.  $+0.13 -0.00$

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Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions unless otherwise specified

MATERIAL: Aluminium

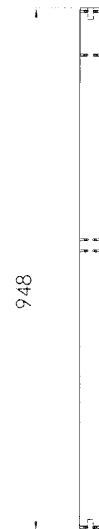
TITLE: Assembly Tube

DESIGN: Part27

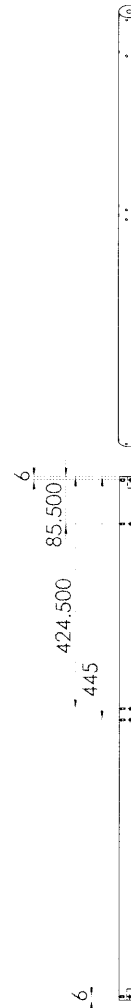
SCALE: SHEET 1 OF 1

38.740 +.00  
-.13

Threaded Hole:  
M19 x 1.5 Thread  
One on each end



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Threaded Hole Pattern:  
M4 x 0.7 Thread

Threaded Hole Pattern:  
M4 x 0.7 Thread

Threaded Hole Pattern:  
M4 x 0.7 Thread

Threaded Hole Pattern:  
M4 x 0.7 Thread

Threaded Hole Pattern:  
M4 x 0.7 Thread

Dimensions: All in mm Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

MATERIAL: **Aluminium**

TITLE

DATE

**Assembly Cylinder 1**

DWG NO

**Part34**

1 of 1

1

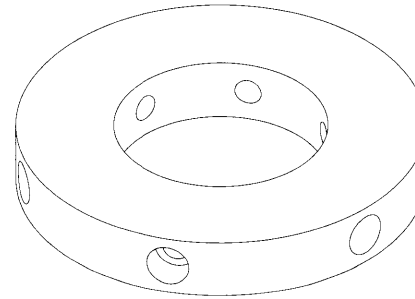
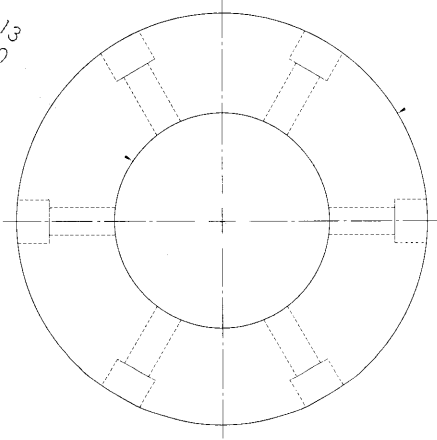
SCALE

SHEET 1 OF 1



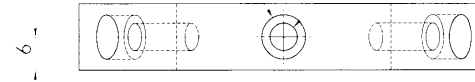
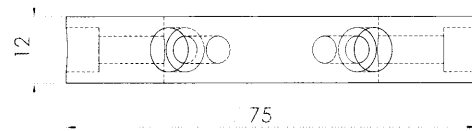
39.260 +.13  
-.00

75 +.00  
-.13



8 +.13  
-.00

Threaded Hole Pattern:  
M5 x 0.7 Thread  
THRU



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: Aluminium

FILED:

Stop

DWG NO:

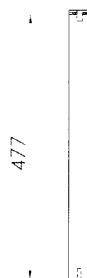
Part38

SHEET 1 OF 1

SCALE:

SHEET 1 OF 1

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39 +.00  
-13

Threaded Hole:  
10M x 1.5 Thread  
Depth: 20 mm

Threaded Hole:  
6M x 1 Thread  
Depth: 25 mm (not to scale)



Threaded Hole Pattern:  
4M x 0.7 Thread  
Depth: 7 mm



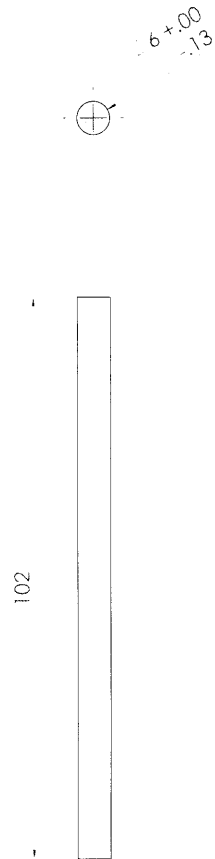
Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions  
unless otherwise specified

MATERIAL Aluminium

REV  
DATE

Assembly Cylinder 3-2

DESIGNED	Part40	Size	Rev
SCALE		A	1
SHEET 1 OF 1			

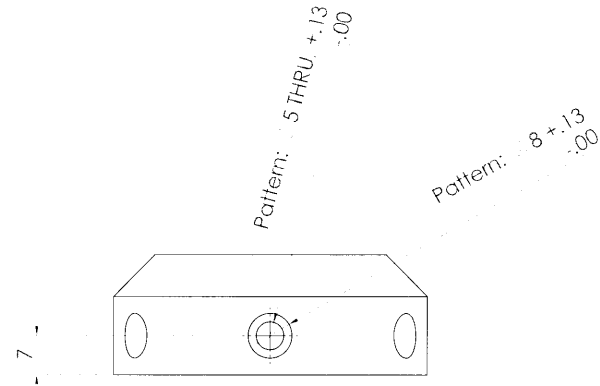
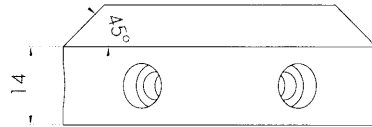
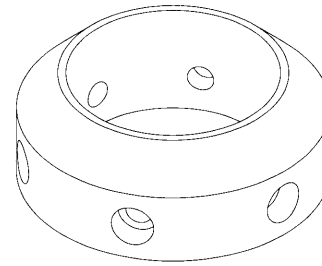
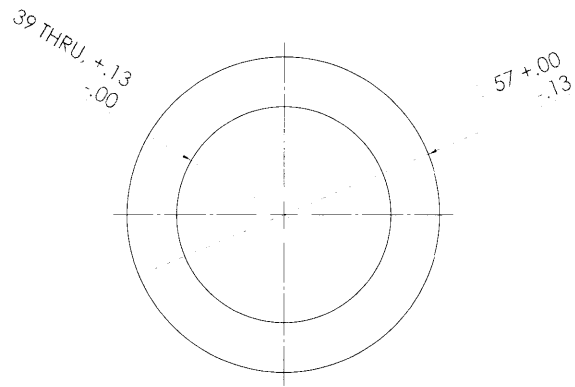


Each end should be threaded with 6M x 1 Thread at a depth of (at least) 20 mm. Please keep the overshoot as small as possible.



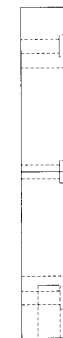
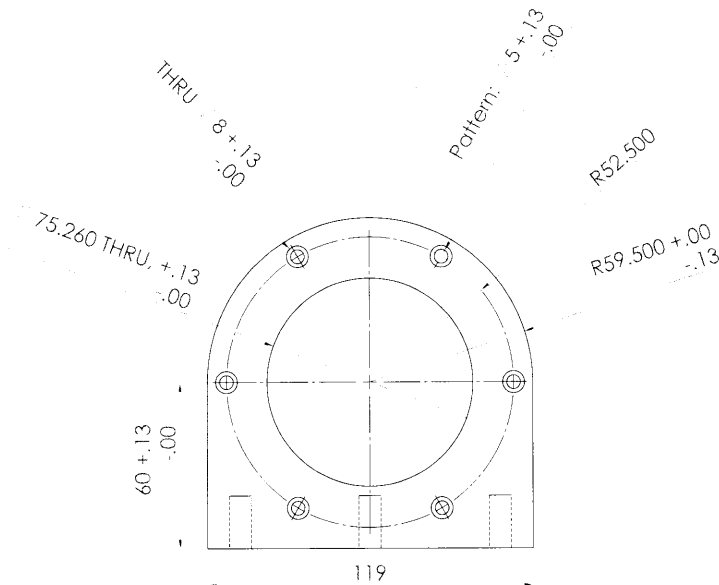
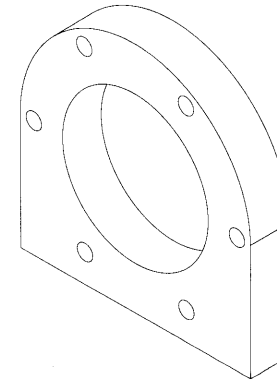
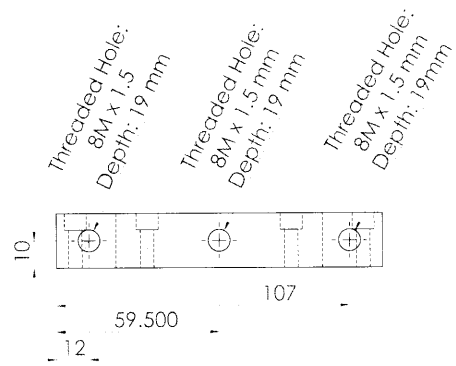
**SolidWorks Student Edition.  
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Dimensions: All in mm Tolerances:  $\pm 0.13$  mm for all dimensions unless otherwise specified  
 MATERIAL: Aluminium  
 TITLE: Connecting Rod  
 Dwg No: Part42 Size: A Rev: 1  
 SCALE: SHEET 1 OF 1



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Dimensions: All in mm Tolerances: $\pm 0.13$ mm for all dimensions unless otherwise specified	
MATERIAL	Aluminium
FILE	
DATE	
Magnet Brace 1	
DRAWN BY	Part43
DATE	
SCALE	SHEET 1 OF 1



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

MATERIAL: Aluminium

TITLE  
DATE

Tube Supporter 1

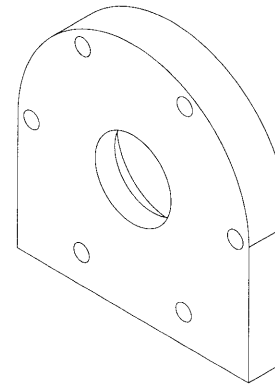
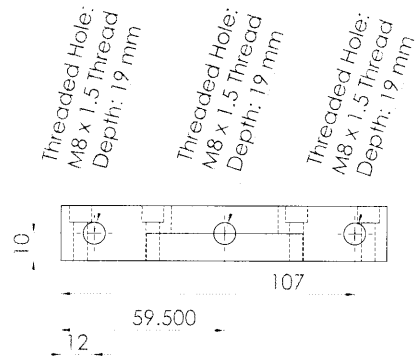
DWG NO.

Part46

Rev  
A 1

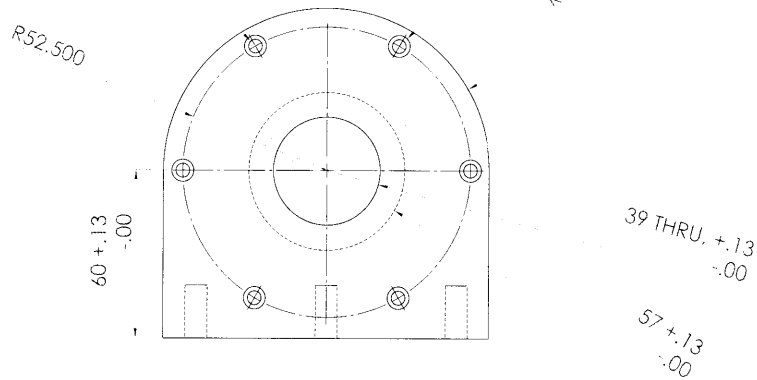
SCALE

SHEET 1 OF 1



Pattern:  
5 THRU, +.13  
-.00

Pattern:  
8 THRU, +.13  
-.00



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions,  
unless otherwise specified.

MATERIAL: Aluminium

TITLE  
DATE

Tube Supporter 2

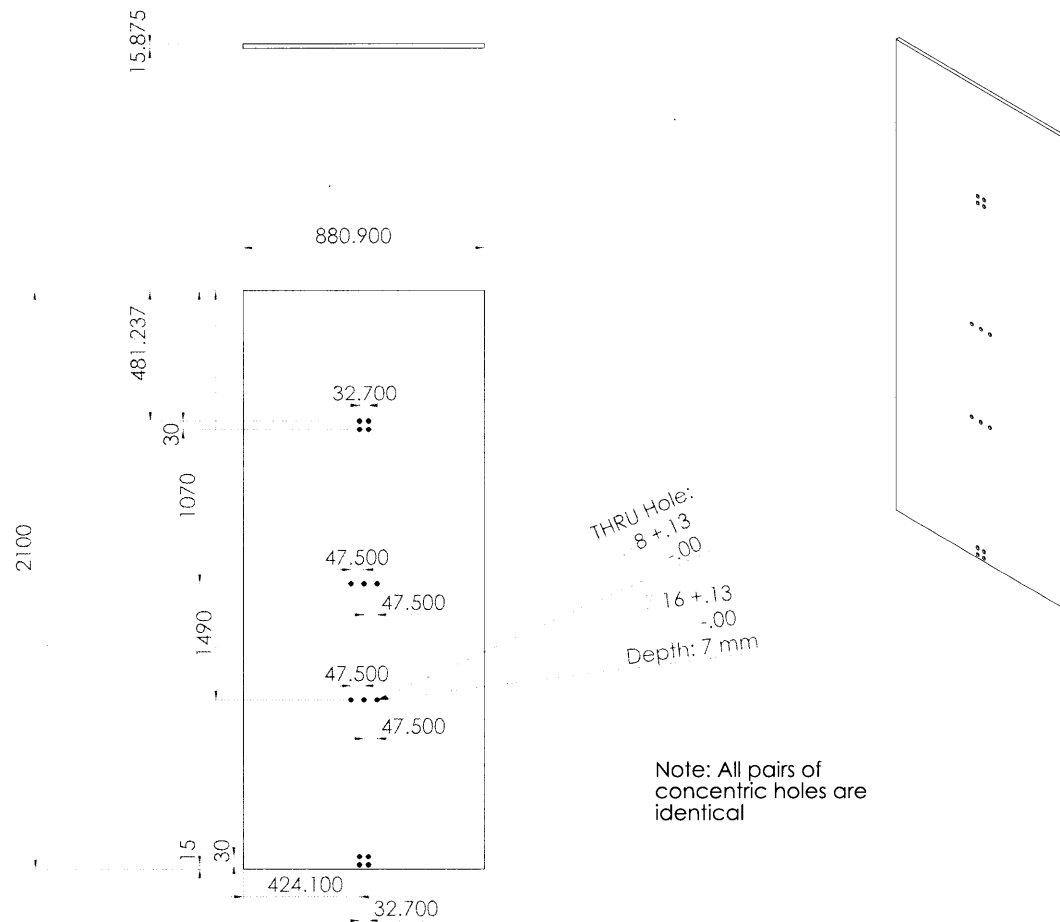
DWG NO

Part48

DATE  
REV

SCALE

SHEET 1 OF 1



**SolidWorks Student Edition.  
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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: Plywood

TITLE

Base Board

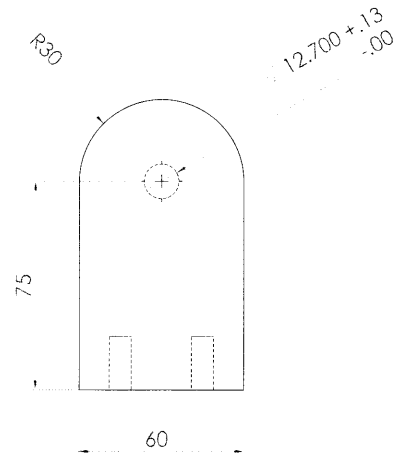
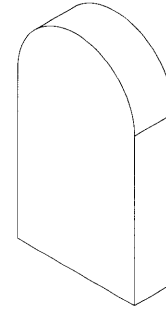
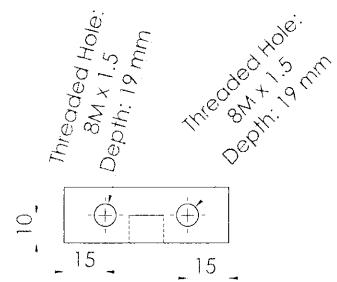
DESIGN

Part49

SHEET 1 OF 1

SCALE

SHEET 1 OF 1



**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions  
unless otherwise specified

MATERIAL: **Aluminium**

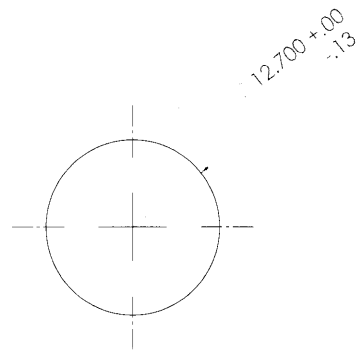
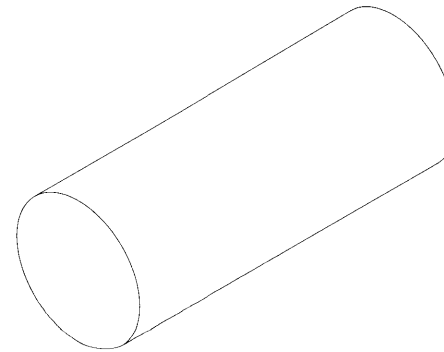
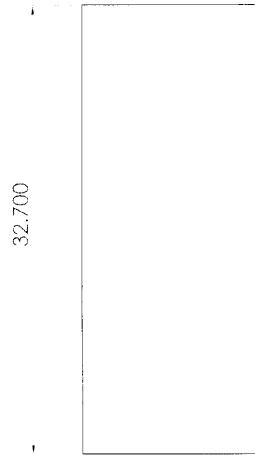
TITLE  
DATE

**Pulley Tower 2**

DRAWING: **Part52** Size: **A** Rev: **1**

SCALE: (SEE 1 OF 1)





**SolidWorks Student Edition.  
For Academic Use Only.**

Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions, unless otherwise specified.

MATERIAL: Aluminium

FILE

DATE

Pulley Pin

DWG NO.

Part53

Rev

A

Rev

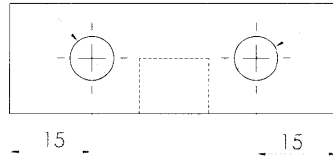
1

SCALE

SHEET 1 OF 1

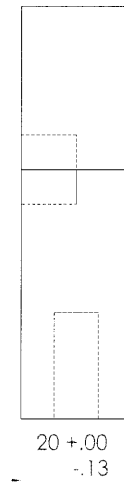
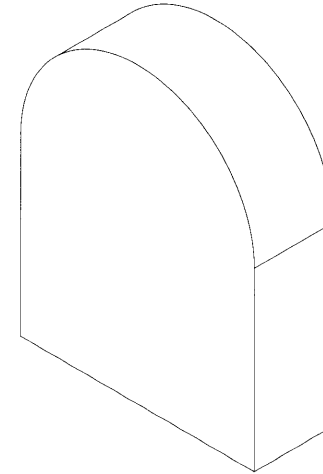
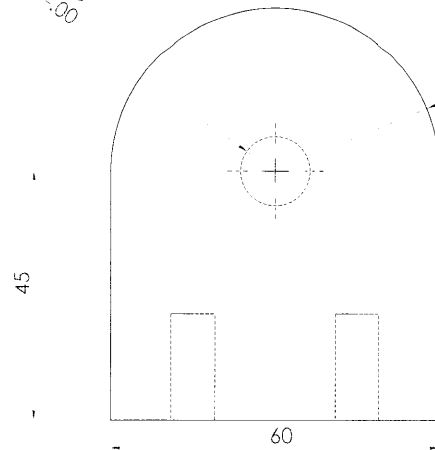
Threaded Hole:  
M8 x 1.25 Thread  
Depth: 19 mm

Threaded Hole:  
M8 x 1.25 Thread  
Depth: 19 mm



12.700 +.13  
-0.00

R30



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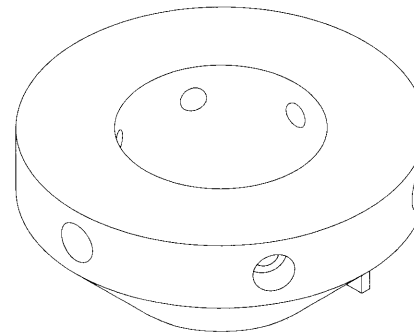
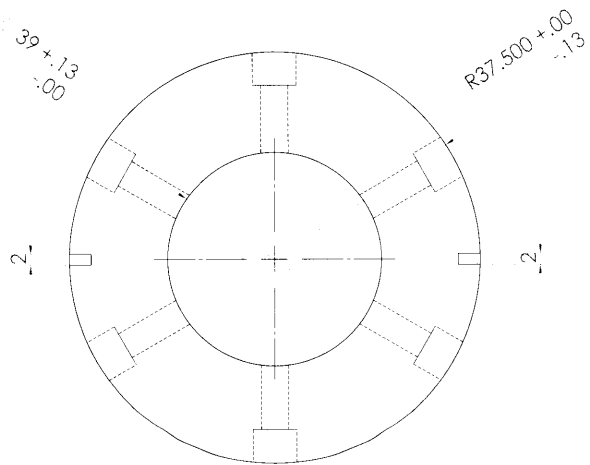
Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: Aluminium

DESIGNER:  
DATE:

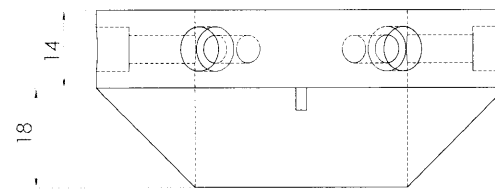
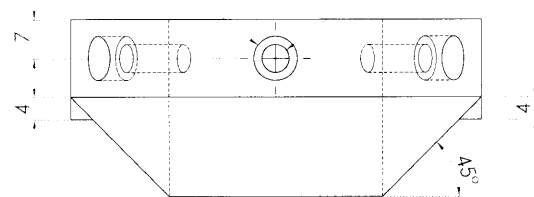
Pully Tower 1

DESIGNED: Part54 User: A Revision: 1  
SCALE: 1:1 SHEET 1 OF 1



Pattern:  
8 +13 -0.00  
Depth: 6mm

Pattern:  
5 THRU +13 -0.00



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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: Aluminium

TITLE  
DATE

Magnet Brace 2

DESIGNED  
BY

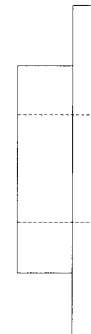
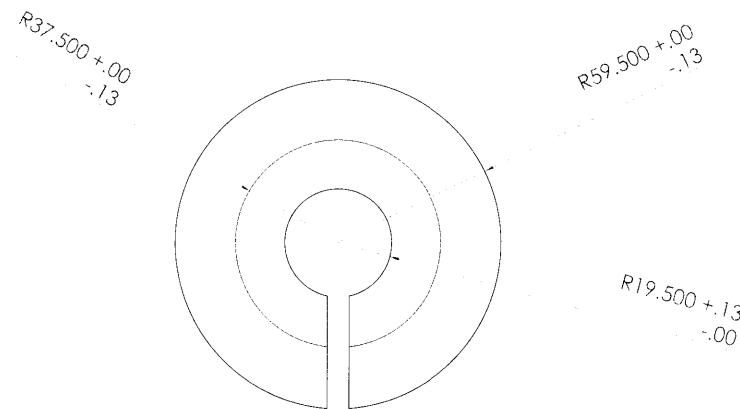
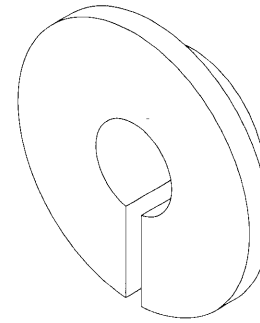
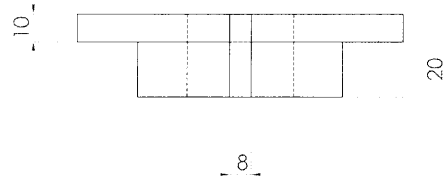
Part55

SHEET  
A

REV  
I

SCALE

SHEET 1 OF 1



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Dimensions: All in mm. Tolerances:  $\pm 0.13$  mm for all dimensions, unless otherwise specified.

MATERIAL: Aluminium

FILE  
DATE

Guide Ring

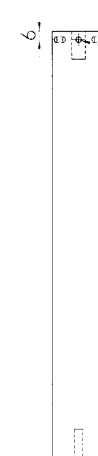
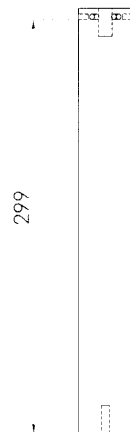
DWG NO: Part56 Size: A Rev: 1

SCALE: SHEET 1 OF 1

Threaded Hole:  
M10 x 1.5 Thread  
Depth: 20 mm

Threaded Hole:  
6M x 1 Thread  
Depth: 25 mm (not to scale)

39 +00  
-13



Threaded Hole Pattern:  
4M x 0.7  
Depth: 7 mm

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Dimensions: All in mm. Tolerances: ±0.13 mm for all dimensions unless otherwise specified.

MATERIAL: **Aluminium**

TITLE  
DATE

**Assembly Cylinder 3**

DWG NO: **Part58** SHEET: **A** REV: **1**  
SCALE: SHEET 1 OF 1